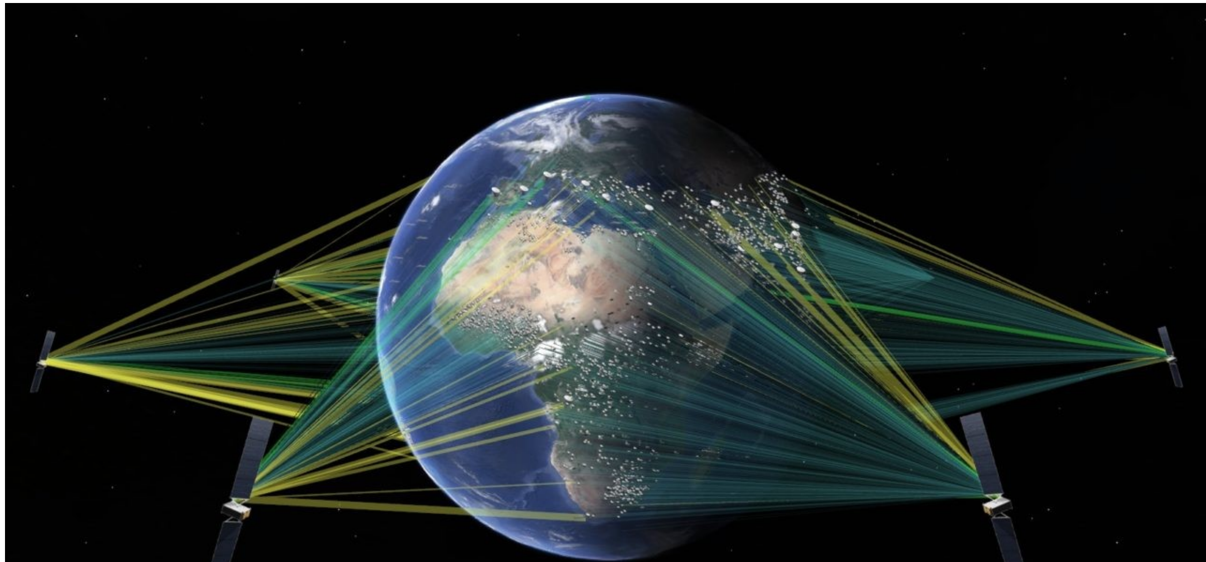
Microwave systems

Microwave Propagation in Free Space and Satellite Communications

Ana Vukovic



http://www.satellitetoday.com/telecom/2017/09/11/boeing-manufacture-seven-meo-satellites-ses-new-network/

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M. Richharia, Satellite Communication Systems: Design Principles, Macmillan Press, 1999.

Propagation effects of radio waves in free space

Learning objectives:

- Dominant propagation effects that affect microwave signal propagation in free space;
- Ray model for fading and sky refraction

Satellite Communications

Learning objectives:

- To be able to design satellite communication system: uplink and downlink design;
- To understand how to minimise the overall noise in the receiver.
- To understand multiple access techniques used in satellite communications
- Assessment, Part 2 : *Design a communication link operating in the defined band to meet C/N and link margin specification (50% of Microwave systems topic)*

Overview

- ✓ Learn about the main effects the electromagnetic wave experiences when propagates in the free space
- ✓ Derive a very simple equation that can be used to define propagation between transmitter and receiver – Friis equation.

Propagation of radio waves in free space

Microwave signals that propagate in free space are affected by :

- Atmospheric attenuation
- Reflection from the earth surface
- Atmospheric refraction
- Over the horizon diffraction

Depending on the dominant mechanism that certain frequencies experience we have:

- Ground Wave propagation
- Sky wave propagation

Atmospheric attenuation

- In the wireless communication radiated power is proportional to $1/R^2$ for the line of sight propagation (R is the distance).

$$P_r \approx \frac{1}{R^2}$$

- Attenuation of EM waves in free space is proportional to $1/R^2$. (Radar losses are two way losses – direct beam and the beam reflected from the object.)

- Compare free space losses with losses in a coaxial cable which are proportional to e^{-R}:

If over distance R we have 100dB attenuation, what would attenuation be over twice that distance using coaxial cables and free space?

If over distance R we have 100dB attenuation, what would attenuation be over twice that distance using coaxial cables and free space?

Over cable: -10log(

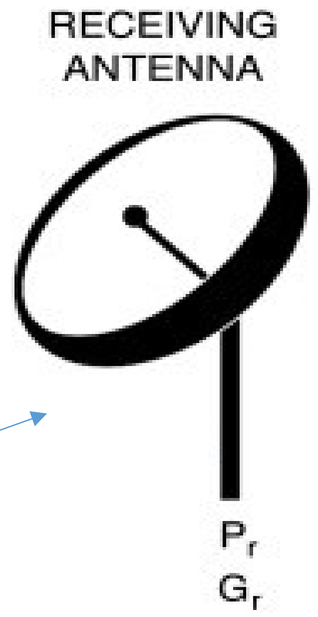
Over free space: -10log(

When we double the distance R we get:

Over cable: -10log(

Over free space: -10log(-10log(-10log(-10log(

Friis Equation – the simplest equation that determines how the received power changes with distance for point-to-point comms systems.



Receiver

R=distance between the transmitter and the receiver

P_r = received power

G_r = gain of the receiving antenna

Transmitter

P_t=transmitted power

G_t =gain of the transmitting antenna

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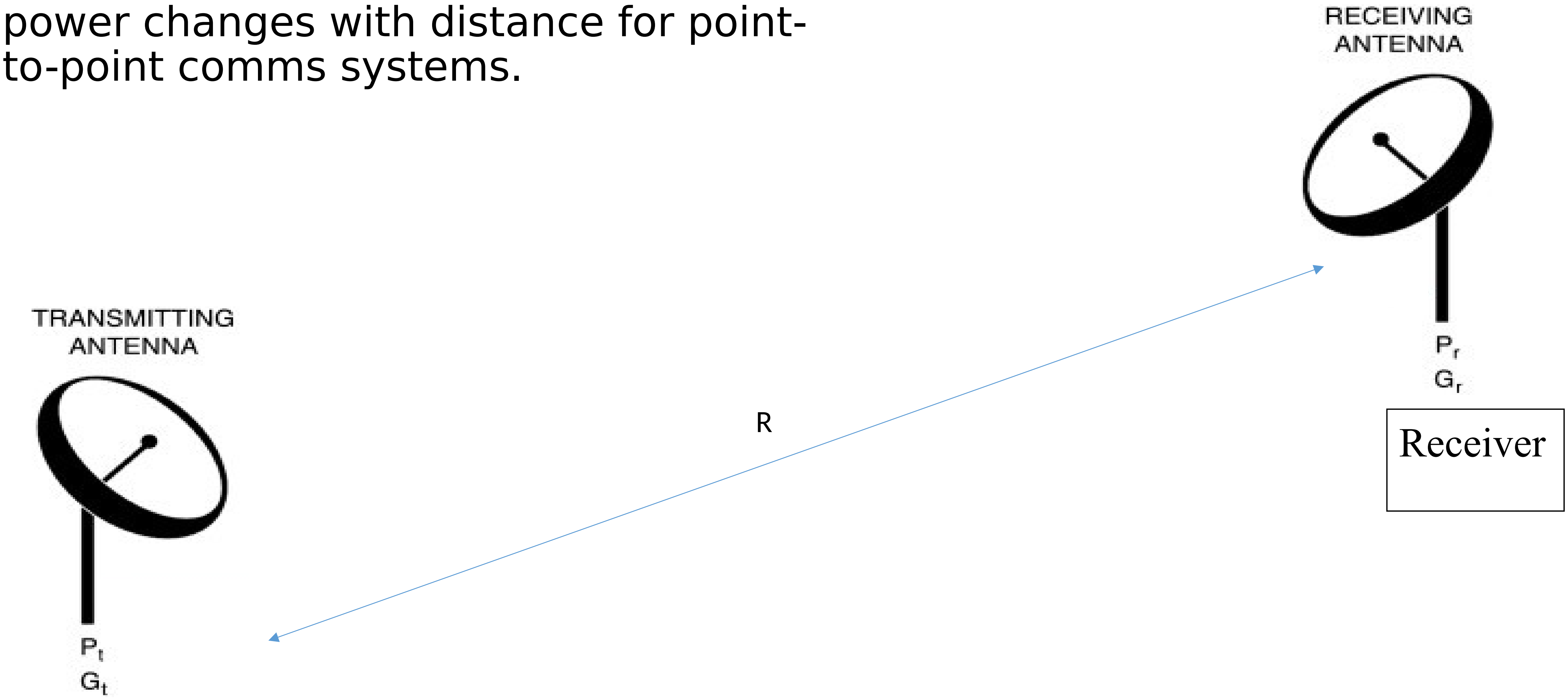


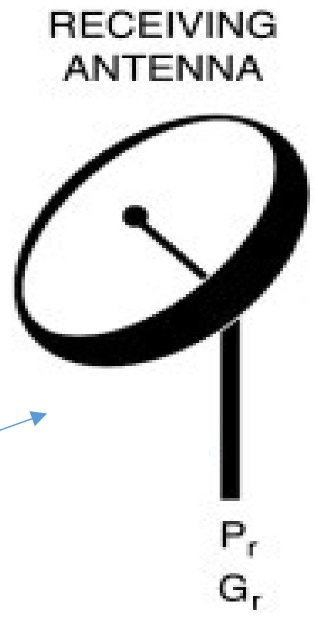
- The product P_tG_t is the *Effective Isotropic Radiated Power* (*EIRP*) and it gives a measure of power flux.
- A minimum value of EIRP is required for each type of receiver.

If the transmitter antenna is isotropic (transmits energy equally in all directions – in free space that would be a sphere), the power density ***at the receiving antenna*** is:

$$P_{den} = \frac{P_t}{4\pi R^2}$$

For a directive transmitting antenna the power density at the receiving end is

$$P_{den} = \frac{P_t G_t}{4\pi R^2}$$



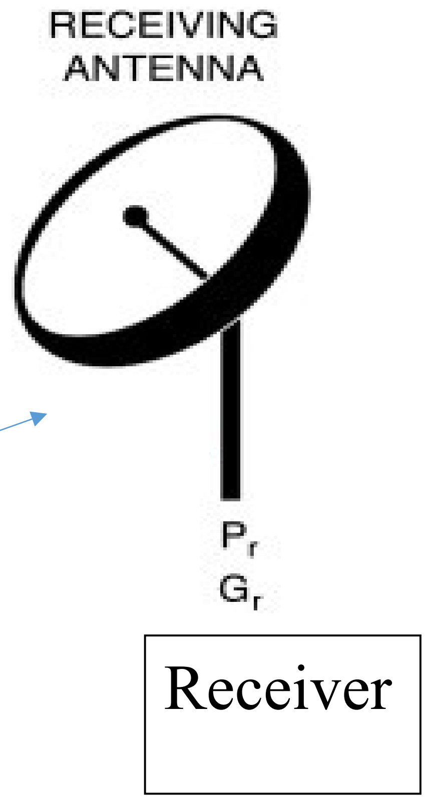
Receiver

R

Transmitter

If the transmitter antenna is isotropic, ***the power density at the input of the receiving antenna*** is:

$$P_{den} = \frac{P_t}{4\pi R^2}$$



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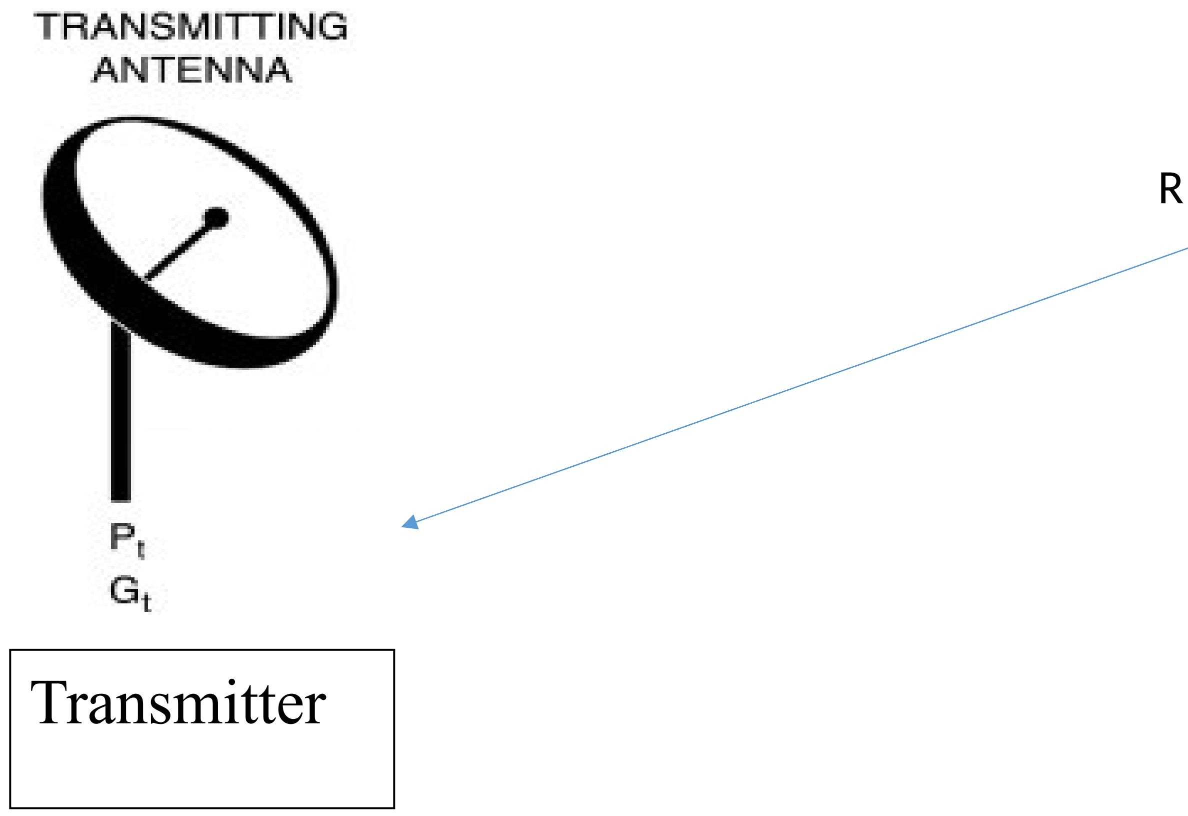


The power P_r delivered to the load (after antenna) is

$$P_r = P_{den} A_e$$

A_e is the effective area of antenna

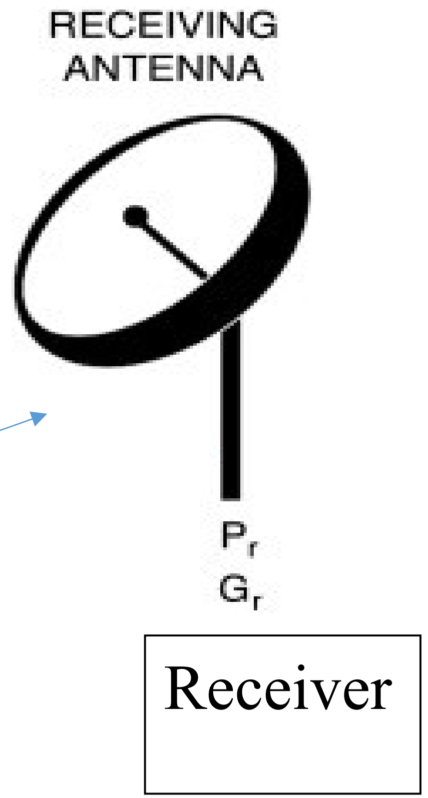
The power P delivered to the load (after antenna) is $\boldsymbol{P_r = P_{den} A_e}$

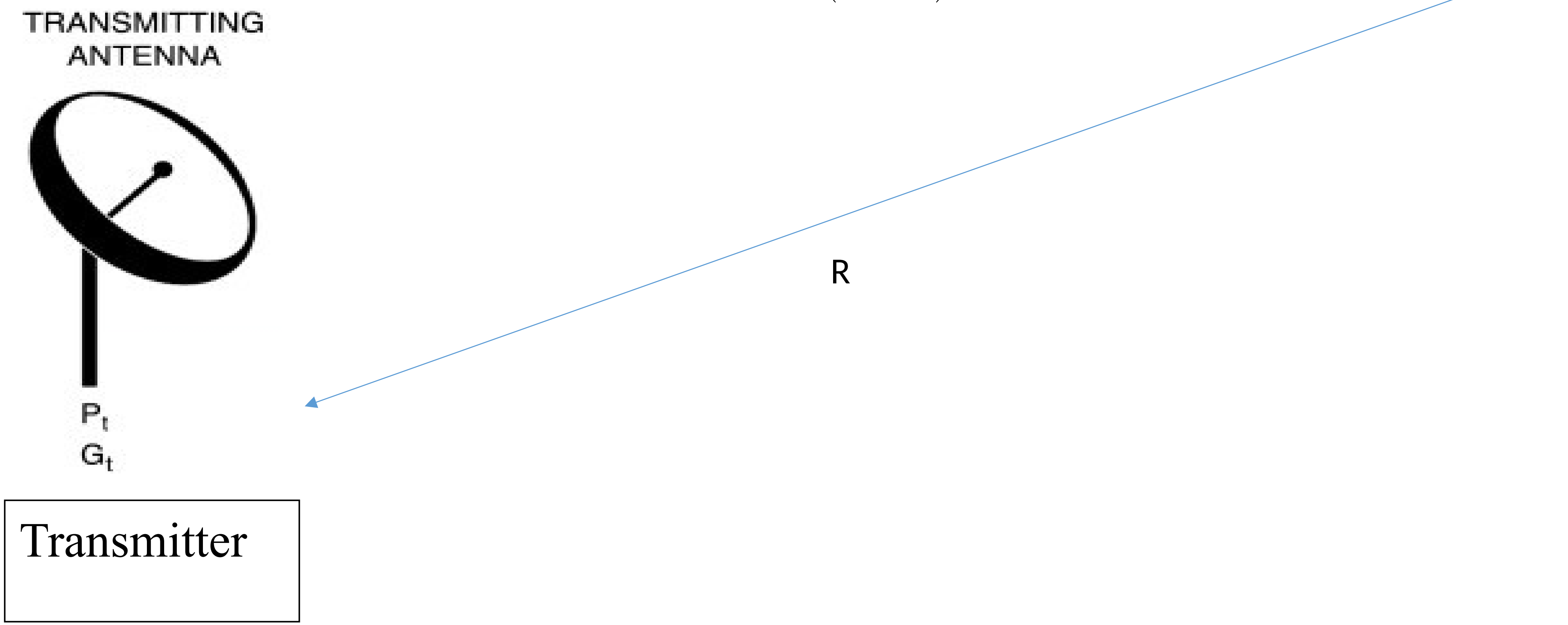
A_e is related to the gain of an antenna and operating wavelength as

$$G = \frac{4\pi A_e}{\lambda^2} \Rightarrow A_e = \frac{G_r \lambda^2}{4\pi}.$$

Friis equation (also known as link equation) is:

$$P_r = G_t G_r P_t \left(\frac{\lambda}{4\pi R} \right)^2$$





Friis (link) equation: $$P_r = G_t G_r P_t \left(\frac{\lambda}{4\pi R} \right)^2$$

- In practice ***the minimum received power is defined by the system requirements***, the Friis equation gives the maximum range for the communication link as:

$$R_{max} = \left(\frac{G_t G_r P_t \lambda^2}{(4\pi)^2 P_{r,min}} \right)^{1/2}$$

- ***The space loss or path loss, SL***, accounts for the spreading of energy through the free space. For the case of isotropic antennas ($G_t = G_r = 1$), SL (in dB) is defined as:

$$SL = 10\log\left(\frac{4\pi R}{\lambda} \right)^2 = 20\log\left(\frac{4\pi R}{\lambda} \right)$$

- ***The link attenuation a (in dB)*** is defined as:

$$\alpha = 10\log\left(\frac{P_t}{P_r} \right) = 10\log\left(\frac{1}{G_t G_r} \frac{4\pi R}{\lambda} \right)^2 = 20\log\left(\frac{4\pi R}{\lambda} \right) - G_t[dB] - G_r[dB]$$

Example 1

- A space probe transmitting and receiving system has a measured noise level at the receiver of $1.2 \cdot 10^{-20}$ W. The transmitted power from the probe is 5W and it is 800 million kilometres from the receiver. The transmitting antenna is isotropic and the effective aperture of the receiving antenna is 850m^2. Calculate the signal-to-noise ratio (in dB) at the receiving antenna. Operating frequency is 150MHz.

****

- Noise power = $1.12 \cdot 10^{-20}$ W
- Transmitted power P_t=5W.
- $R=800 \cdot 10^{6} \cdot 10^{3}$m
- $f=150MHz=150*10^{6}Hz$
- $A_e=850m^2$
- Signal/noise =?
- Gt- isotropic antenna

****

Example

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- $f=150MHz=150*10^{6}Hz$
- $A_e=850m^2$
- Signal/noise =?
- $G_t=1$ – gain of isotropic antenna or Gt(dB)=0

****

We know noise power and now need to calculate received power in order to find signal to noise ratio.

Use Friis equation: $P_r = G_t G_r P_t \left(\frac{\lambda}{4\pi R} \right)^2$

$$\lambda = \frac{c}{f} = \frac{3 \cdot 10^8}{150 \cdot 10^6} = 2\,m$$

==2669

– for isotropic antenna – radiates uniformly in all directions

$$P_r = G_t G_r P_t \left(\frac{\lambda}{4\pi R} \right)^2$$

W

Signal/noise =

To conclude

- The power of electromagnetic signal in free space reduces as $1/R^2$ where R is the distance
- Friis equation is the simplest equation that determines how the received power changes with distance for point-to-point comms systems.

$$P_r = G_t G_r P_t \left(\frac{\lambda}{4\pi R} \right)^2$$

Propagation effects of radio waves in free space

Microwave signals that propagate in free space are affected by :

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- Over the horizon diffraction

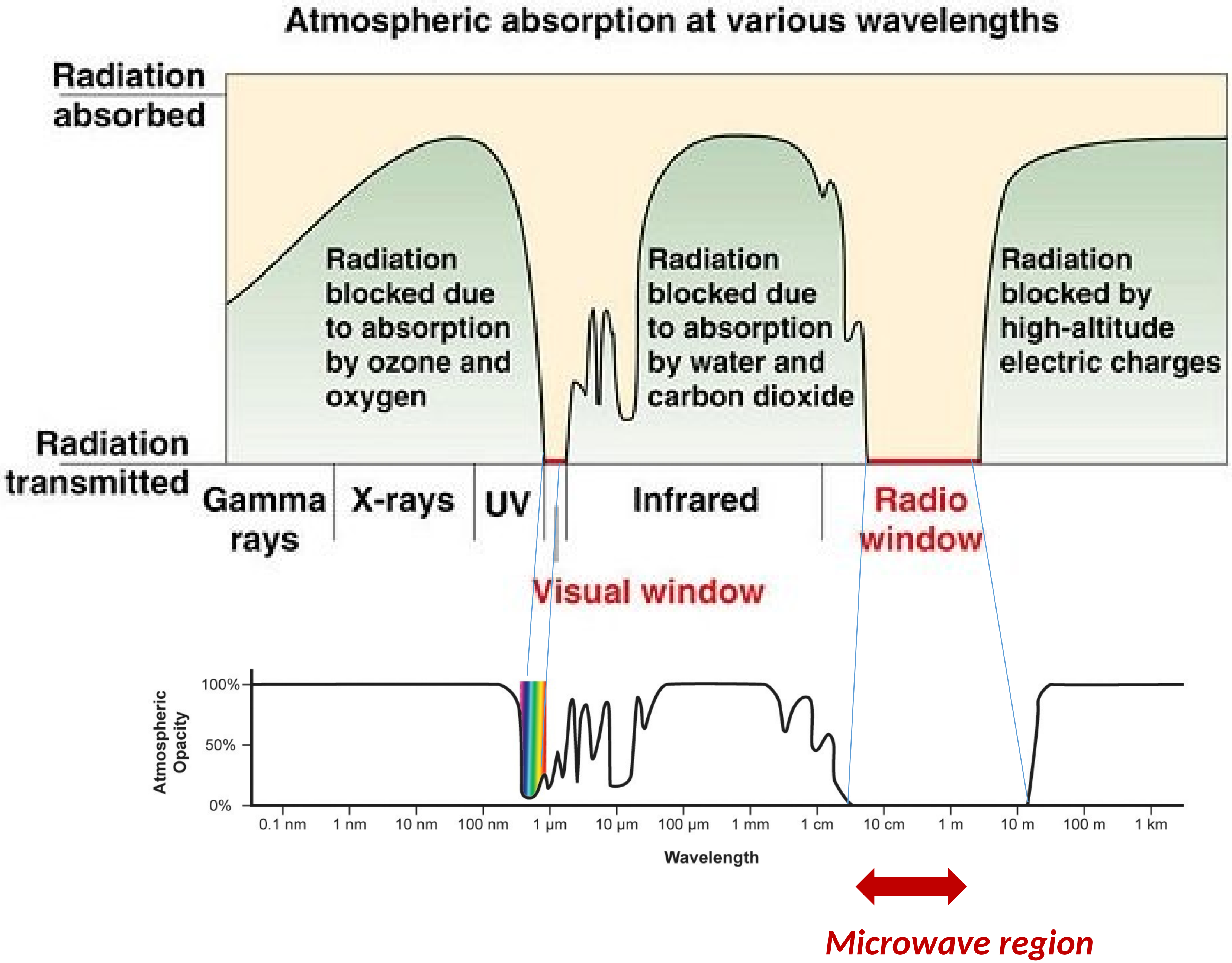
Depending on the dominant mechanism that certain frequencies experience we have:
- Ground Wave propagation
- Sky wave propagation
- Space wave propagation

EM waves are absorbed by atmospheric particles such as water vapour, carbon dioxide, ozone;

Humidity, air pressure, rain and fog also affect the propagation of waves.

The areas of EM spectrum that are absorbed by atmospheric gasses are known as ***absorption bands***. But there are also areas of the EM spectrum for which the atmosphere is transparent – ***atmospheric "windows"***.
In the microwave region most waves propagate unaffected;

Presence of the earth surface (land or water), roughness (planes or mountains) and curvature also affect the propagation;



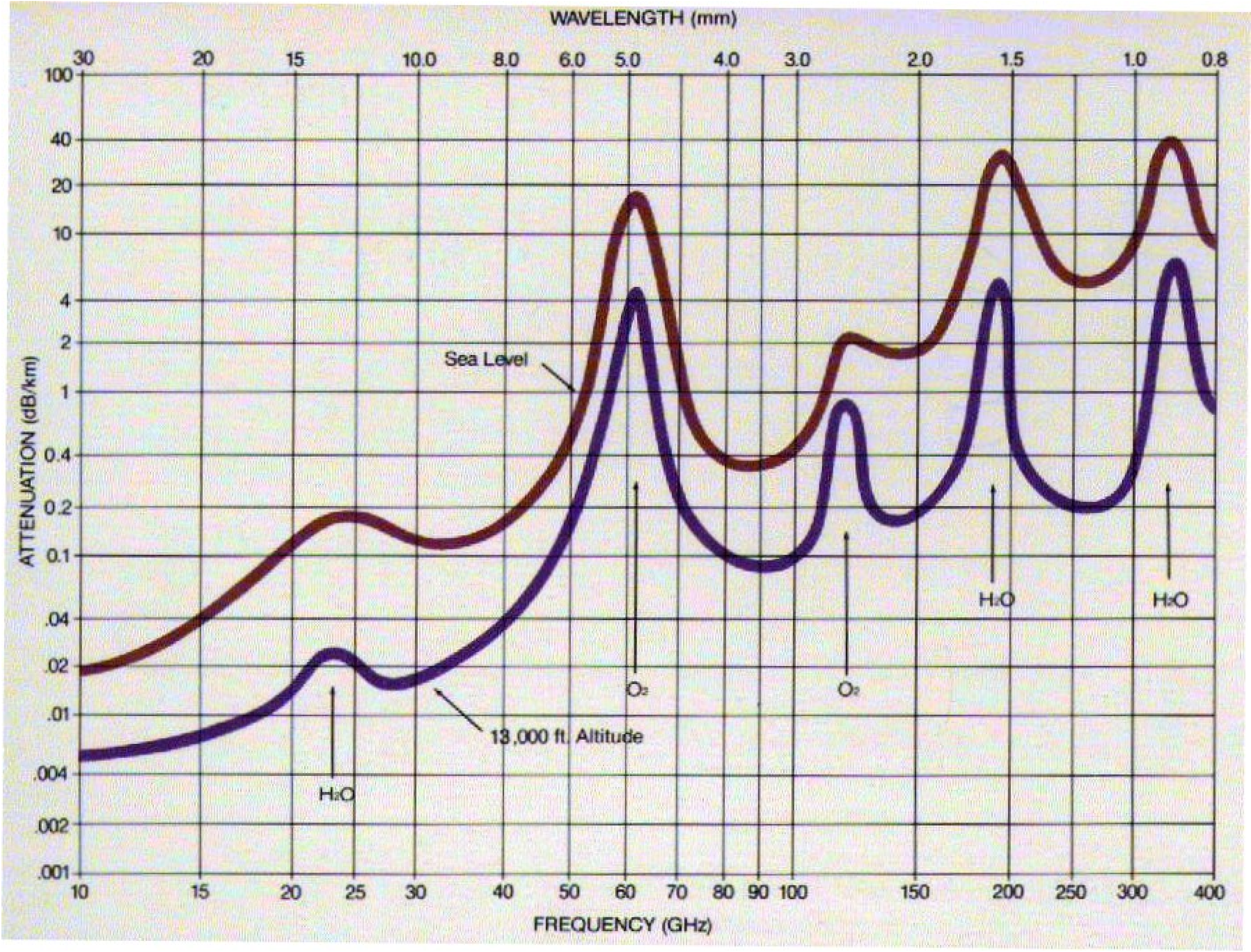
Radio waves propagate through atmosphere with little attenuation.

Maximum attenuation peaks occur when the frequency coincides with the molecular resonances of water or oxygen.

At 35GHz, 94GHz and 140 GHz radar and comms systems can operate with minimum loss;

Remote sensing of atmosphere is done at a point of maximum atmospheric absorption (20-55GHz).

Spacecraft- to- spacecraft comms is done at 60GHz – reduced interference or eavesdropping from earth.

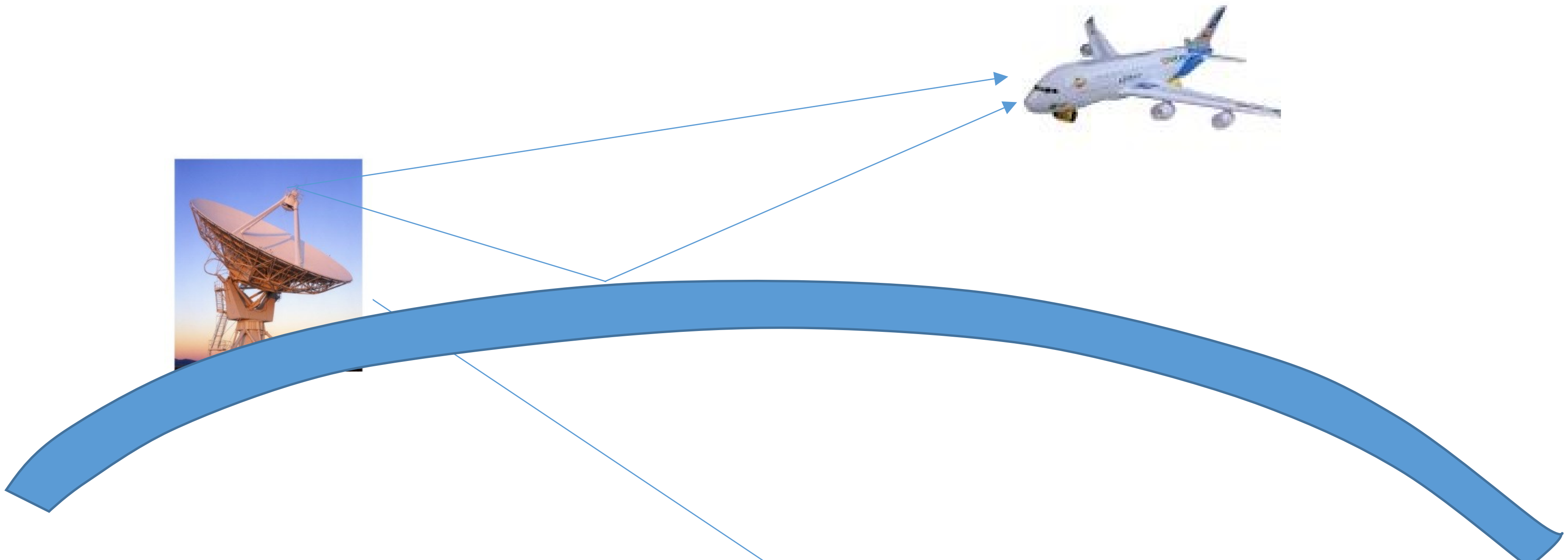


Average atmospheric absorption of millimeter waves

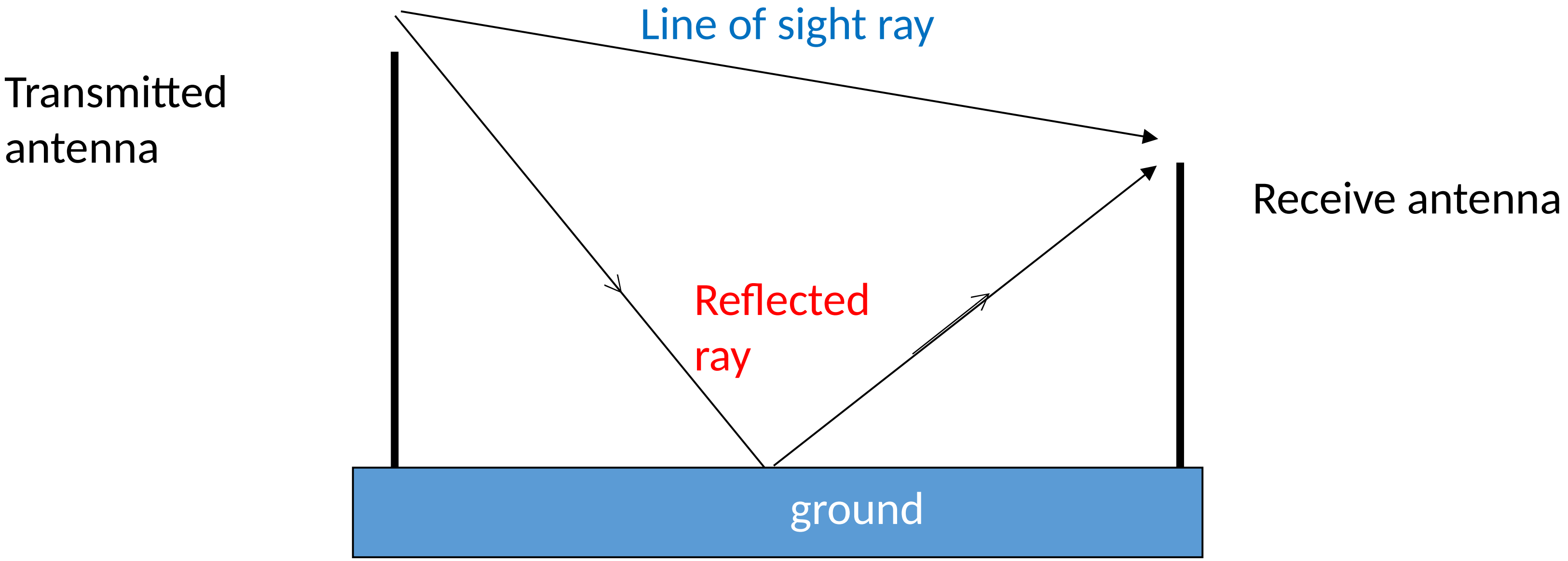
Attenuation increases as frequency is increased – high frequency waves are not well suited for long distance communication

Reflection from Earths surface – ground effects

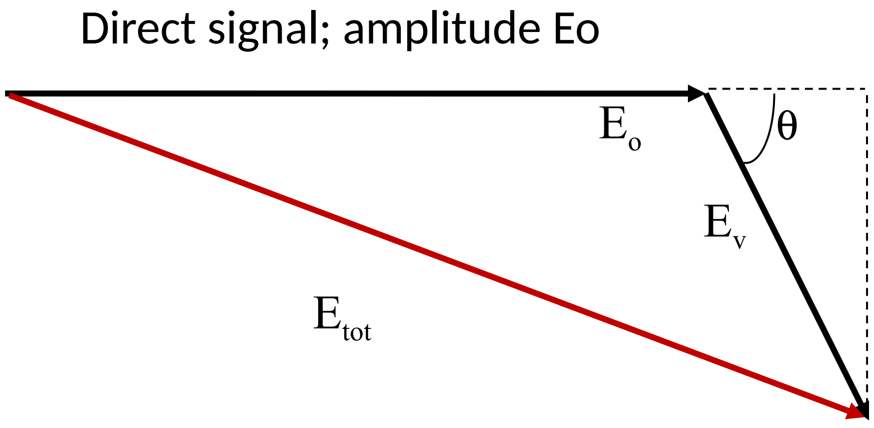
- Microwave propagation is affected by the presence of the earth's ground;
- Waves reflect from the ground
- The reflected wave is generally smaller in amplitude because it travels longer distance and because the ground is not a perfect reflector;
- The received signal at the target will be a sum of two waves and depending on the relative phases of these waves the resultant signal can be greater or smaller than the direct wave alone – this phenomenon is known as ***fading***; Slow and fast fading – depending on how quickly these changes occur.
- So let's see how phase difference between 2 signals can affect the overall strength of reception!



Two ray model of fading



At the receive antenna direct and reflected signals can be represented as vectors of certain amplitude and phase.



Reflected signal; amplitude Ev; phase difference θ from the direct signal;

$$|E_{tot}| = \sqrt{(E_o + E_v\cos\theta)^2 + (E_v\sin\theta)^2}$$

$$\left|\frac{E_{tot}}{E_o}\right| = \sqrt{1 + \frac{2E_v}{E_o}\cos\theta + \left(\frac{E_v}{E_o}\right)^2}$$

It is assumed that the magnitude of E_v remains constant, **but that its phase, θ**, relative to E_o changes. In fact, we will assume that all values of θ are equally likely ($0<\theta<\pi$)

So assume Eo=Ev and just look at the effect of phase difference between direct and reflected wave:

=2

$$\left|\frac{E\,tot}{E\,o}\right| = \sqrt{\left(1+\left(\frac{E\,v}{E\,o}\right)^2\right)} = \sqrt{2}$$

=0

Signals in phase, θ=0. Resultant signals is magnified by a factor of 2!

Signals are orthogonal, θ=90 deg => resultant signals is magnified by a factor of 1.4!

Signals are in antiphase, θ=180 deg => resultant signal is 0!

This ratio is changing in time so we can specify median value.

The ***median*** value of any time variable quantity is that value above which the quantity is for 50% of time. Or to rephrase this, for 50% of the time, the variable quantity is greater than the median value. Here, the median value of θ is clearly $\pi/2$, so that the median value of the total received signal is

$$\left|\frac{E_{tot}(median)}{E_o}\right| = \sqrt{1+\left(\frac{E_v}{E_o}\right)^2} \quad \Longrightarrow \quad \frac{E_{tot}}{E_{tot}(median)} = \frac{\sqrt{1+2\frac{E_v}{E_o}\cos\theta+\left(\frac{E_v}{E_o}\right)^2}}{\sqrt{1+\left(\frac{E_v}{E_o}\right)^2}}$$

As θ increases, the received signal gets smaller.

Example

If Ev/Eo =0.75, what is the probability of the signal E_T dropping 10dB below the median value of the received field strength?

$$\left|\frac{E_{tot}}{E_o}\right| = \sqrt{1 + {}^{2E_v}\!/\!_{E_o}\cos\theta + \left(\frac{E_v}{E_o}\right)^2}$$

For median value: $\left|\frac{E_{tot}}{E_o}\right|_{median(\theta=\pi/2)} = \sqrt{1 + \left(\frac{E_v}{E_o}\right)^2} = 1.25$

$$20\log\left|\frac{E_{tot}}{E_o}\right|_{median(\theta=\pi/2)} = 20\log(1.25) = 1.94dB$$

10 dB below =>1.94-10=-8.06dB. Than results in E_{tot}/E_o=0.395.

$$\left|\frac{E_{tot}}{E_o}\right| = 0.395 = \sqrt{1 + 2\cdot 0.75\cdot\cos\theta + (0.75)^2} \Rightarrow \theta = 0.887\pi$$

For $0.887\pi<\theta<\pi$ of 11% of time, the total value is below median value by 10dB or more.

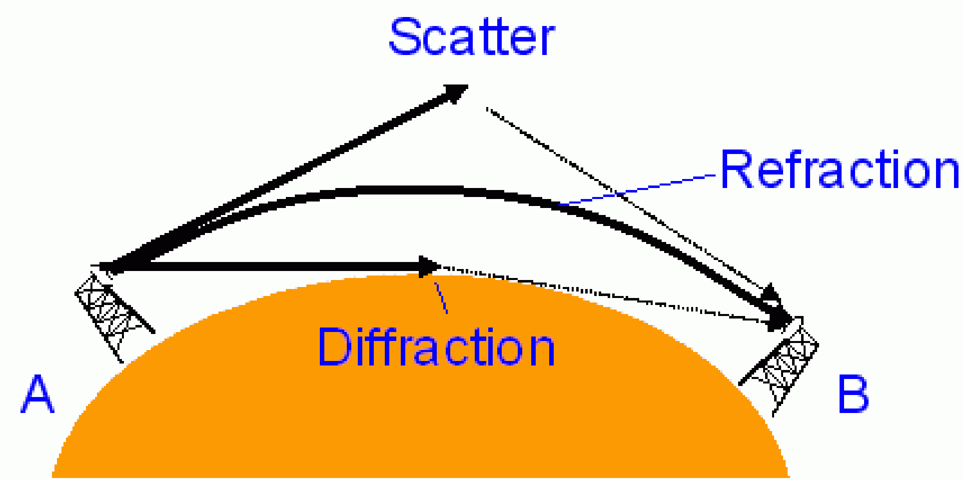
b) Above what value is the signal for 99% of the time?

$0.99\pi<\theta<\pi$

For $\theta=0.99\pi$ => the signal strength is E_{tot}/E_o=0.251 or -11.9dB.

Atmospheric diffraction, scattering and refraction

- **Atmospheric scattering** – from the particles and inhomogeneities in air that diffuse a portion of incident wave in all directions. Scattering can cause attenuation problems in radar and measuring devices.
- **Atmospheric diffraction** happens when radio wave scatters energy in the vicinity of the boundary at the horizon and extending a range beyond the horizon. Diffraction is stronger in the presence of hills, mountain or buildings. In a radar system unwanted reflections often occur from terrain vegetation, buildings and surface of the sea and these clutter echoes degrade or mask the return of the true target. In mapping or remote sensing such clutter returns may constitute the desired signal.
- **Atmospheric refraction** or bending of the waves can also extend the range of radar or communication system beyond the limit imposed by the presence of earth's horizon. It is a direct consequence of the fact that refractive index of atmosphere reduced with the height and as it decreases it bend the waves (Snell's law).

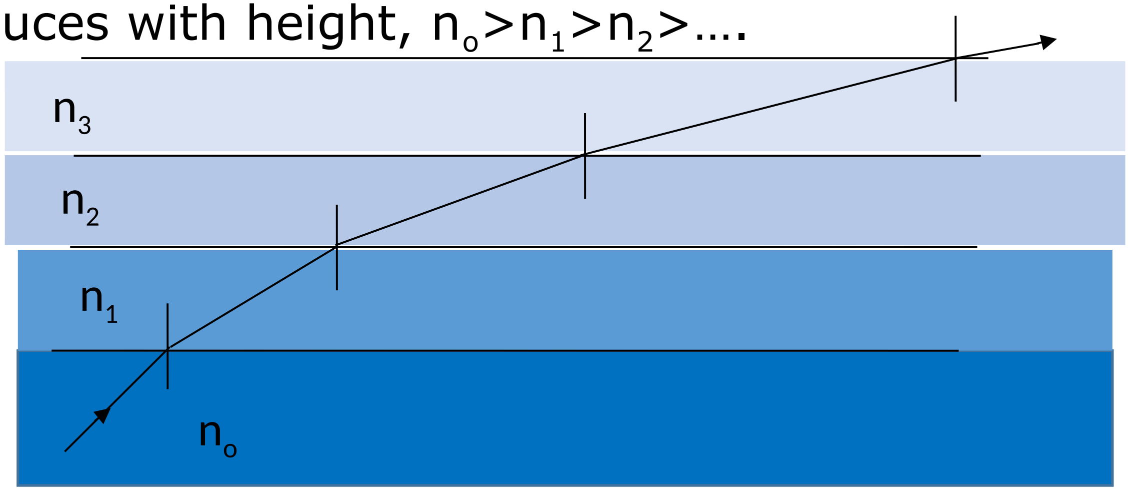


Atmospheric refraction

- The propagation path can be modelled as though the atmosphere were a sequence of distinct layers of differing refractive indices.
- Higher layers of atmosphere receive more energy from the sun which helps the atmosphere molecules to ionise – this acts to reduce the density of higher layers of atmosphere.

- The refractive index reduces with height, $n_o > n_1 > n_2 > ....$

Stratified refractive index model of ionosphere!

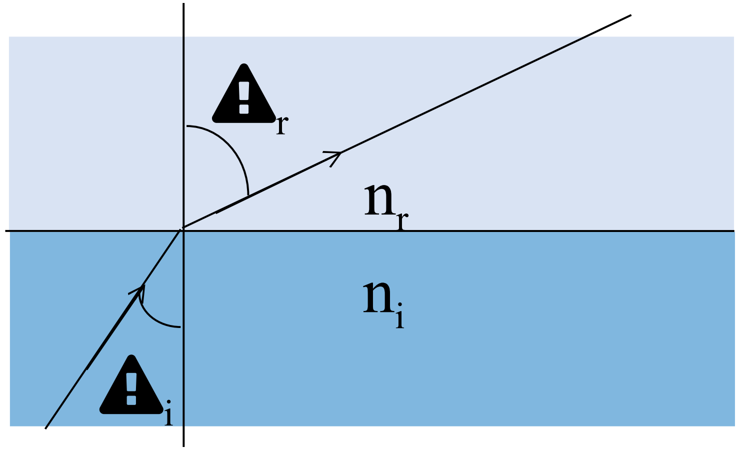


Q: How does the ray bend if the ray comes from a denser material (n_i>n_r)?

Q: How does the ray bend if the ray is incident from a less dense material (n_i<n_r)?

- At each interface we can apply Snell's Law

$$n_i \sin(\theta_i) = n_r \sin(\theta_r)$$

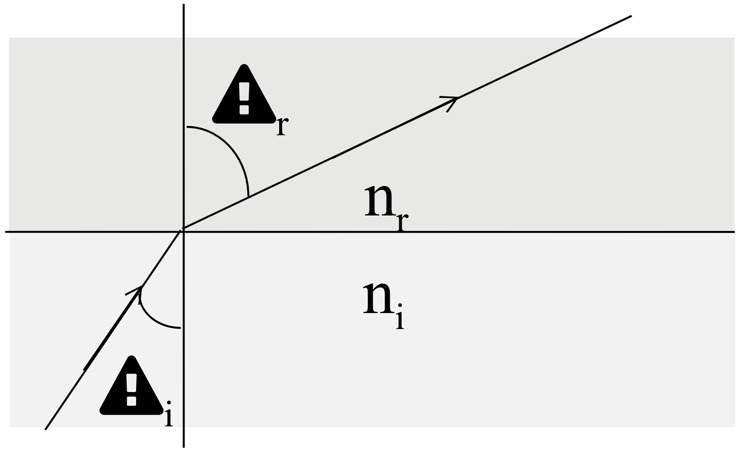


- The refractive index reduces with height this causes the sky wave refraction.

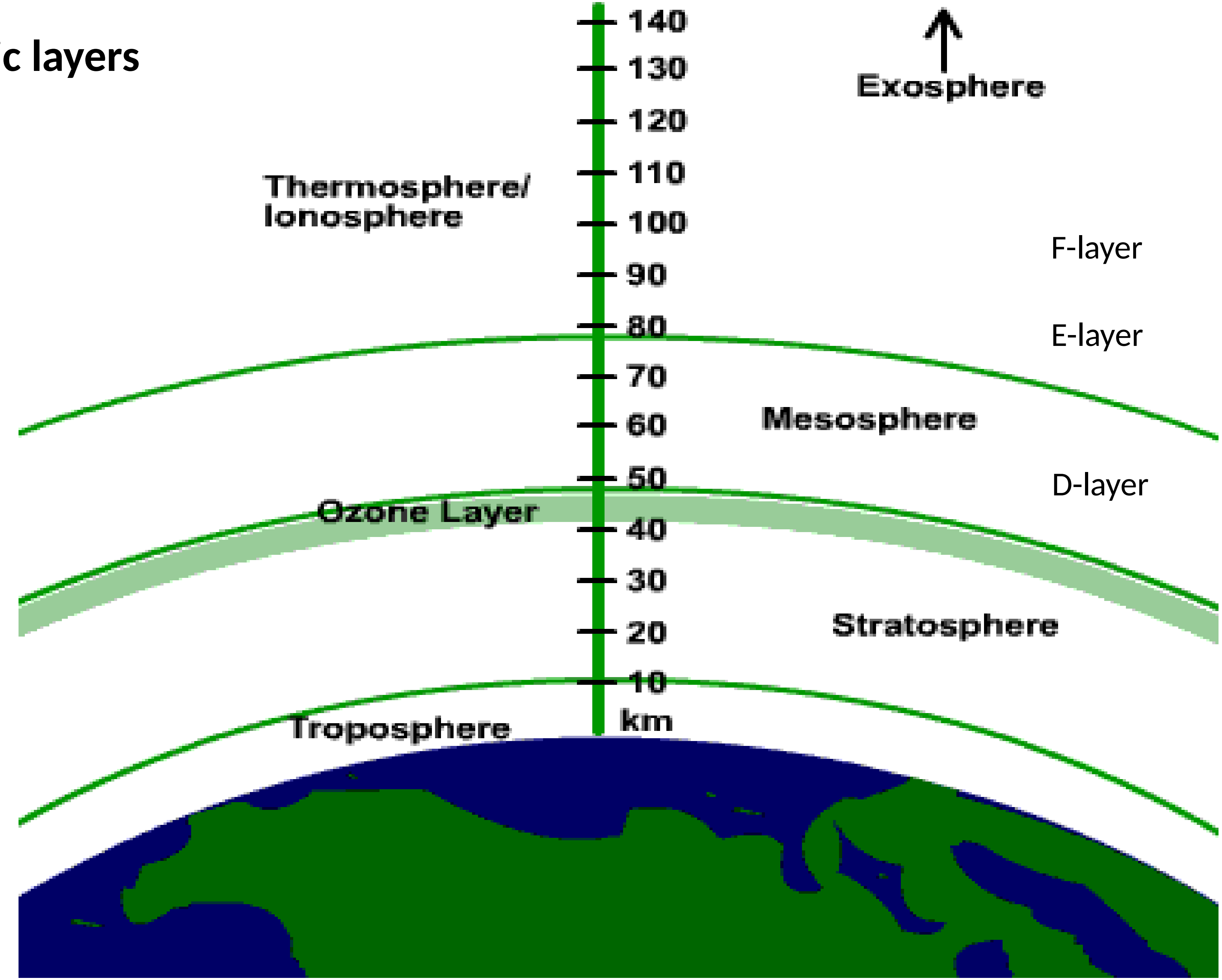
- For reflection to occur require θ_r = 90^o, i.e.,

$$\frac{n_r}{n_i} = \sin \theta_i$$

- The lower levels of the atmosphere have n_i = 1. Therefore reflection occurs at height where n_r = sin θ_i



Atmospheric layers

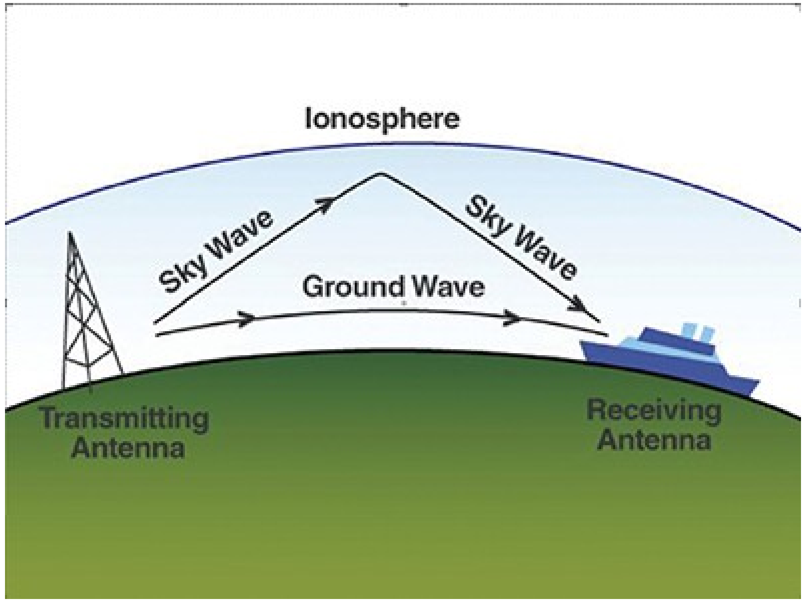


Ground Wave Propagation

- Frequency band (3kHz-3MHz); The waves propagate between the surface of the earth and ionosphere.
- Microwave signals get reflected from the non-homogenous layers in troposphere at the height of 20 km above the earth.
- Troposphere and stratosphere act as a waveguide – **terrestrial waveguide**!! There is no need for LOS

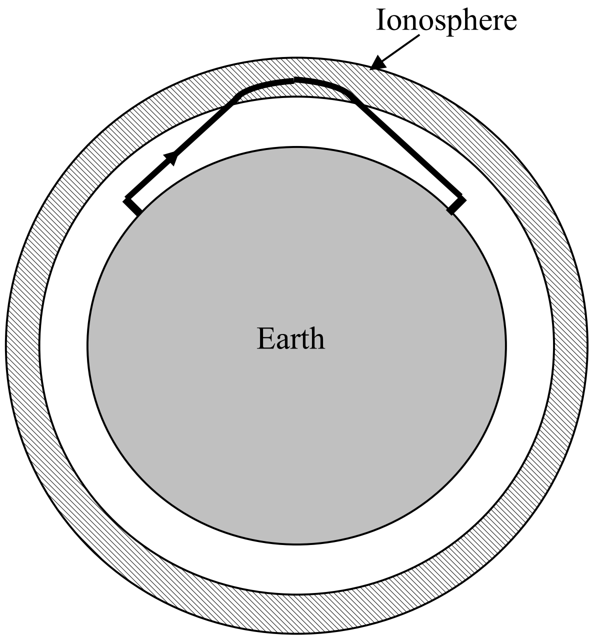
- Attenuation for VLF is low, hence long distance transmission possible; Low frequencies limit data rate – useful for long distance navigation systems. Antennas are physically large but electrically small (i.e. compared to the wavelength).
- High transmitting power, high antenna gain and low receiver noise are required since lots of energy gets lost. Often radiated power is several hundreds of kW.

- Position of ionosphere varies with time of day – affects propagation; Conductivity of the ground affects range – e.g. seawater has a much higher conductivity than dry land. Longer distances can be established using ionospheric reflection (100 km above the earth).



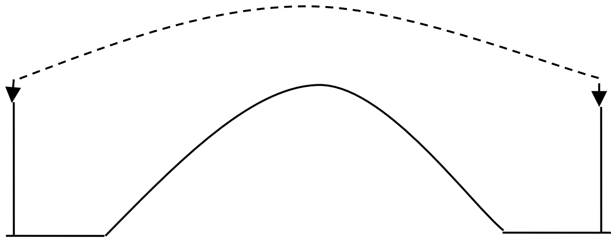
Sky Wave Propagation

- Conductive ionospheric layers reflect and refract RF signals; Over horizon coverage!
- Starts with MF (300kHz-3MHz) often causing interference between sky and ground waves, especially at night.
- Most effective for HF (3-30 MHz), and doesn't happen much at higher frequencies
- Can get single or multiple hops.
- Layers in the upper atmosphere can receive sufficient energy, mainly from the sun, to enable molecules to become ionised.
- Because there are relatively few free electrons and positive ions around they can exist for a relatively long time before recombination .
- These ionised layers can cause bending of EM waves incident upon them. Under certain circumstances bent high frequency waves, that would normally have passed through into space, are reflected (strictly refracted) back to earth.
- Variations in atmospheric properties (such as temperature and density) and the amount of radiation received cause the atmosphere to be stratified with D,E and F layers in ascending order.
- These layers are subject to both daily and seasonal variations and also changes in solar activity; The D and E layers occur mainly in daytime only. The F layer is perhaps the most useful for communications, particularly at night when it may divide into F_1 and F_2 layers.

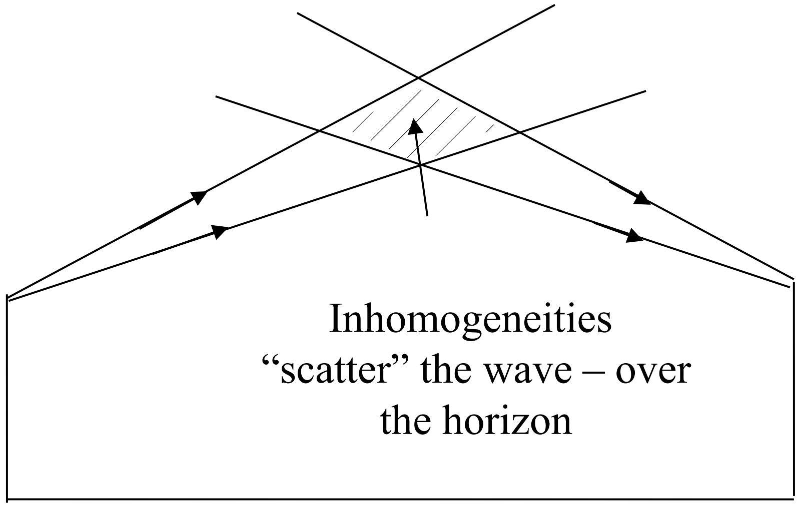


Space Wave Propagation

- Reflection and multi-path effects due to buildings, trees, etc.
- Diffraction effects over hills, etc!



- Atmospheric absorption at higher frequencies limit range (can be good!)
- Tropospheric scattering can be a problem but sometimes useful.



Satellite Communications

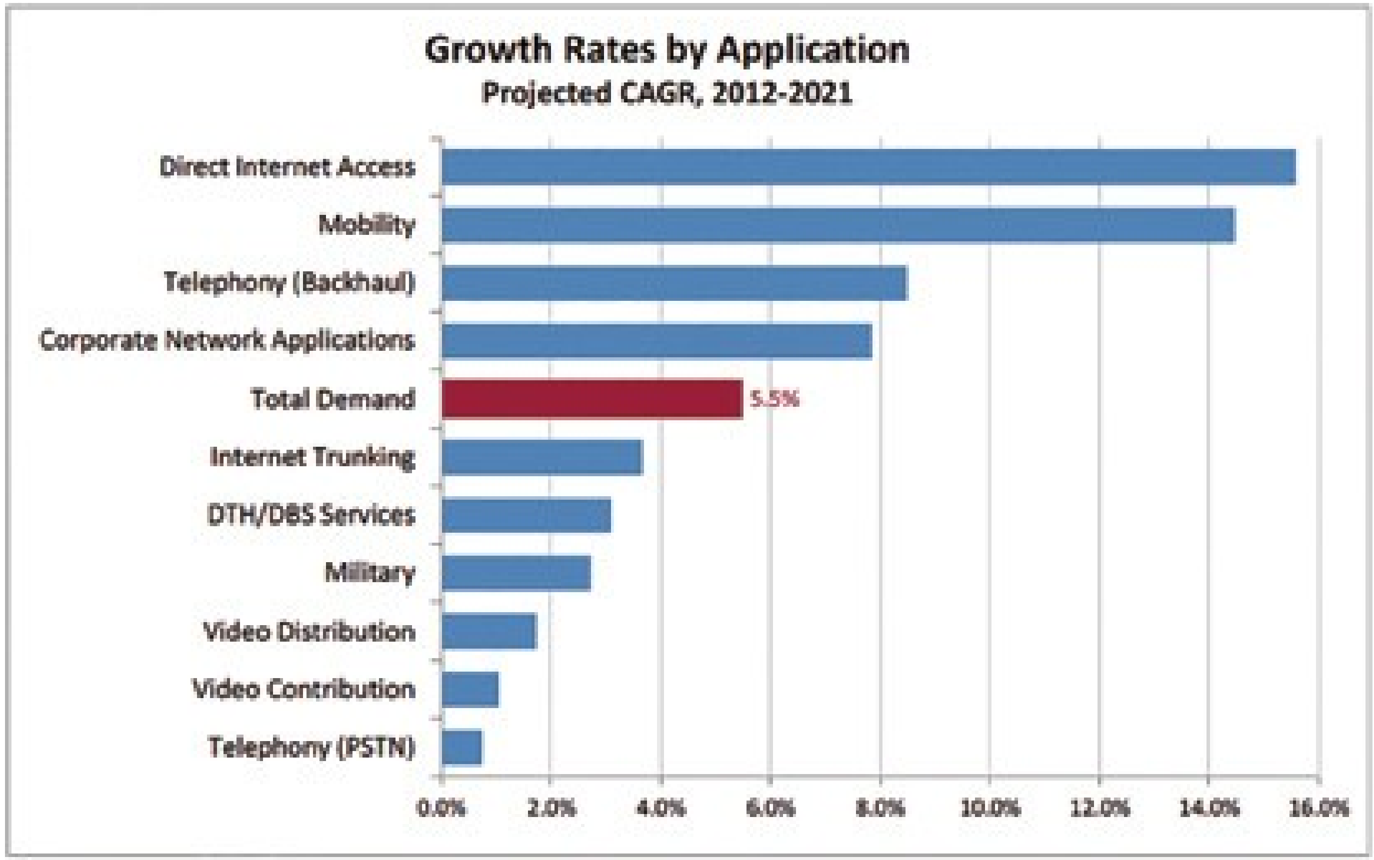
We will now focus on satellite communications and:

- Learn how to design satellite communication system: **uplink and downlink** design;
- Losses in satellite comms are high (high distances, atmospheric attenuation) and received signal is very weak. To get good signal to noise level we need to understand how to minimise the overall noise in the receiver.
- To understand multiple access techniques used in satellite communications

In today's presentation we will cover some basic information on satellite systems (types of satellites, frequency bands, simple principle of operation) and introduce different types of satellite antennas

Satellite communications

- Used for voice, data and video communication.
- Originally developed for long distance telephone service.
- DBS-TV (Direct Broadcasting Satellite – TV) and distribution of video signals to cable TV networks made $17B in revenues in 1998.



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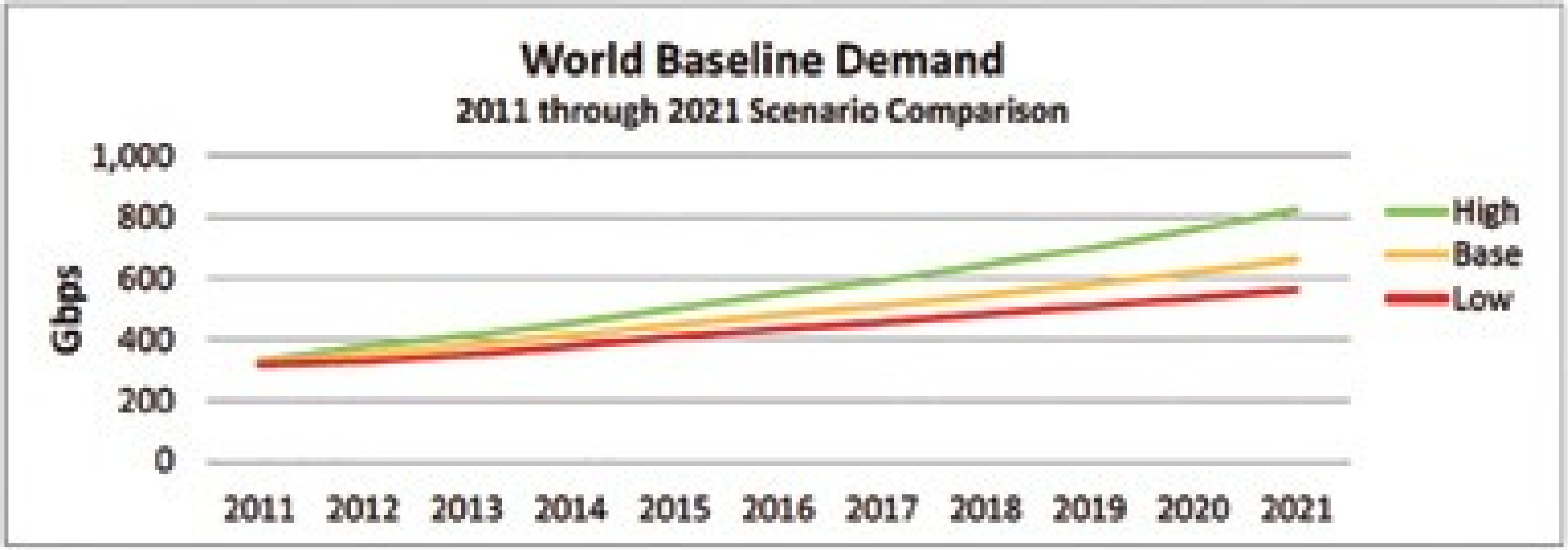
- Satellites compete with optical fibres in carrying voice data and video. A single optical fibre can carry 4.5Gbps – similar to the largest GEO satellite. Fibre has advantages that is laid in bundles (increase in capacity) but satellites are more flexible at the delivery point.



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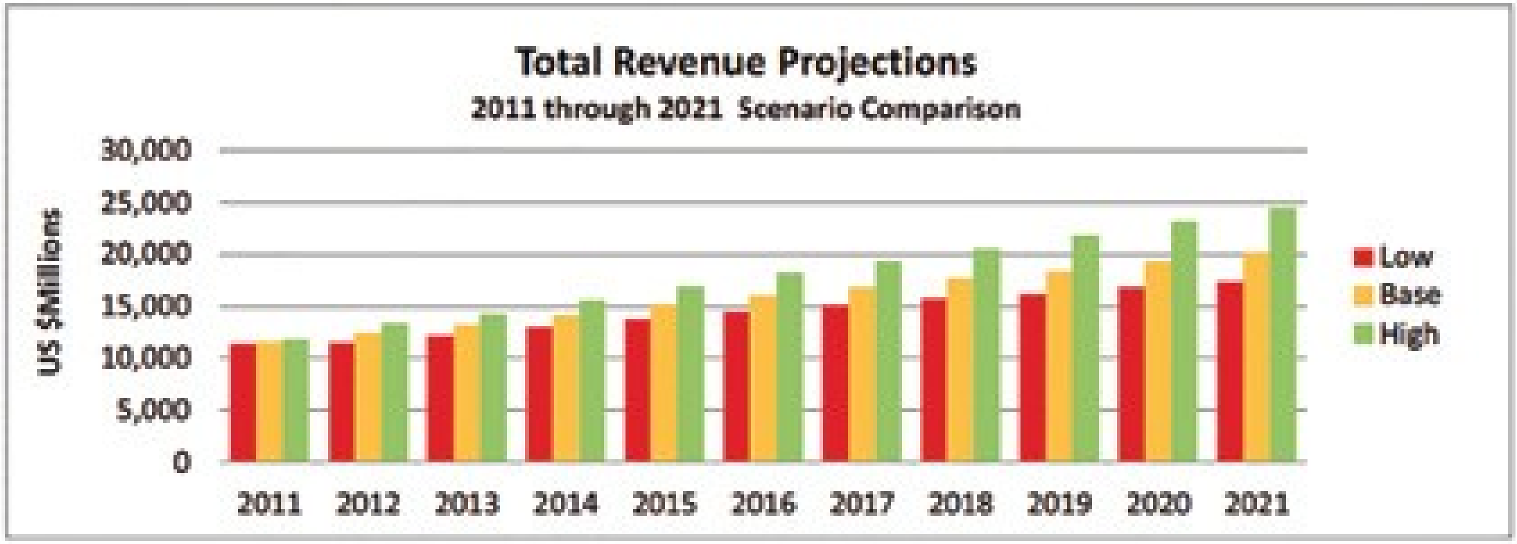
- The revenue for a satellite must exceed $20million per year to make it profitable.



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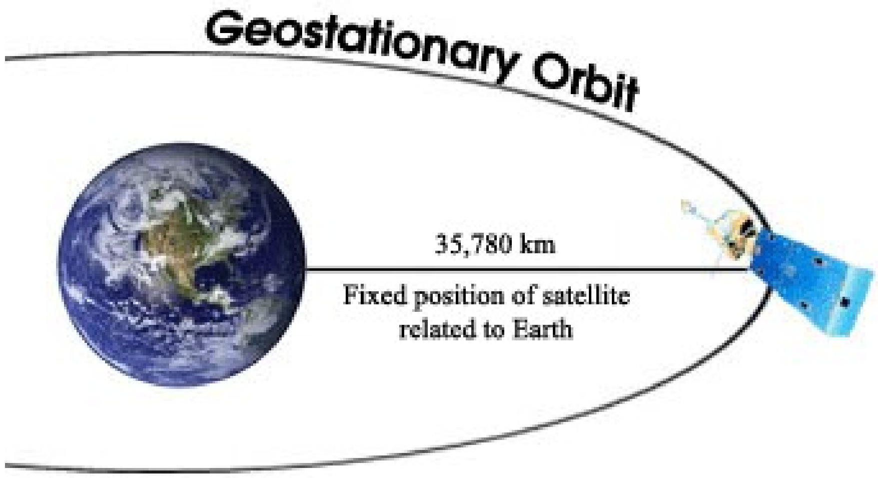
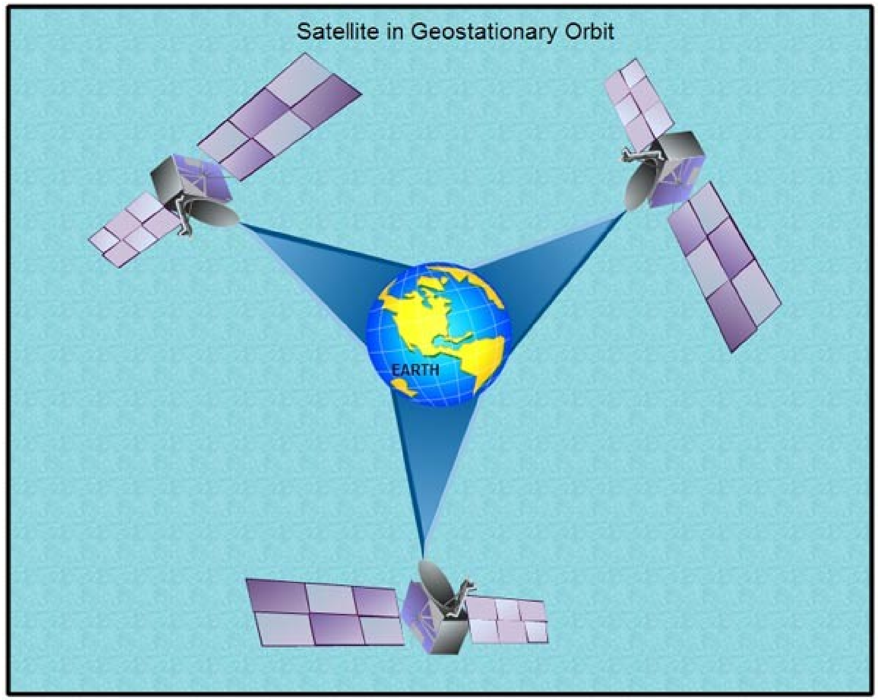
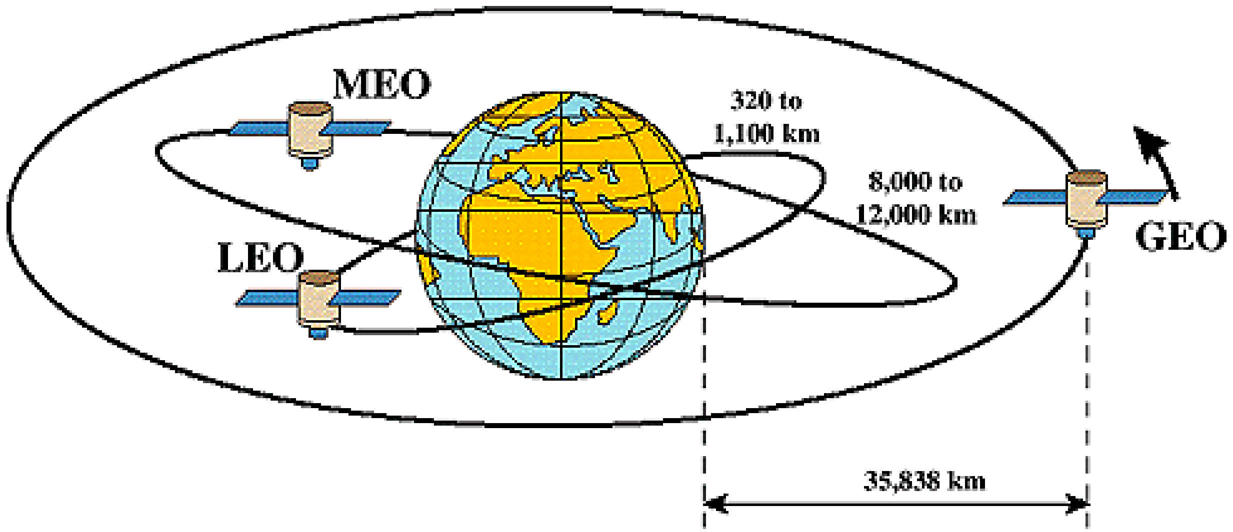
- Satellite system is an extension to terrestrial system with exception that the transponder is in the space.
- Satellites act as repeater: a receiver linked to the transmitter that can receive signal from one station, amplify it and re-transmit to another.
- Majority of comms satellites are in geostationary orbit at 35780km. Signals that arrive at the satellite are very weak due to attenuation of the radio signals. Equally, signals received on earth from satellites are also weak – limits on the electrical power on satellites that rely on solar power. Satellite comms require high power transmitters, high modulation speeds, efficient solar cells, low noise receivers.
- Satellite comms can be established with a fixed station or with mobile or laptop computer.
- Two satellites can connect two points separated by 12000km.
- Three satellites can cover major population centres in the world.



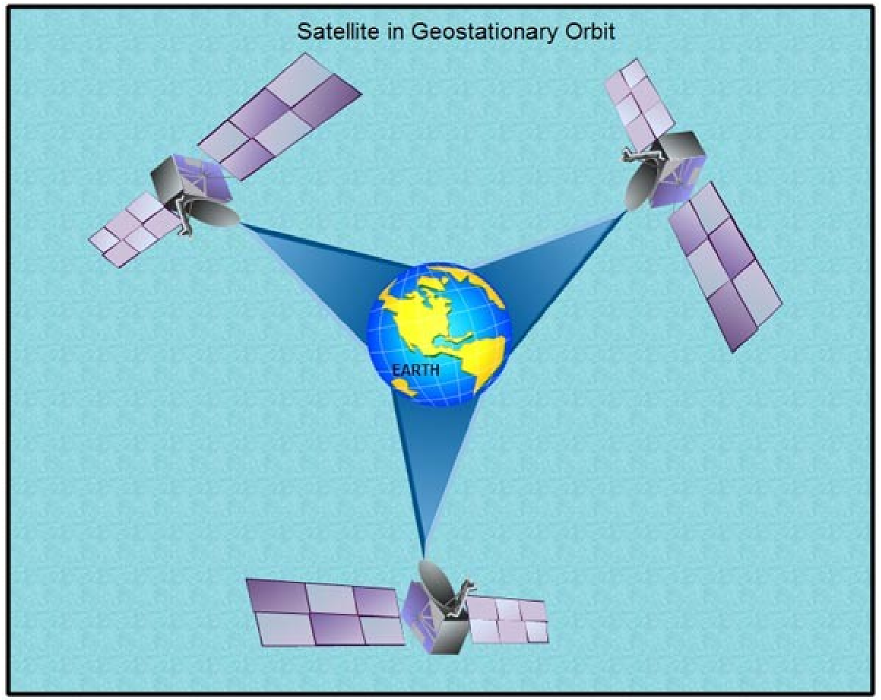


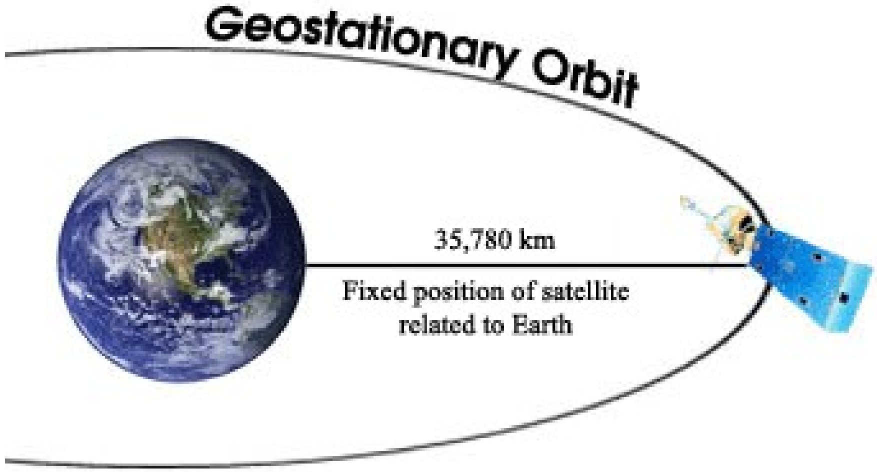
- Geostationary orbit (GEO) is preferred for high capacity comms satellite systems because a satellite in GEO orbit is stationary over a fixed point on the ground.
- A single GEO satellite can serve a whole continent!
- GEO satellites have been supplemented by Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) satellites – for satellite telephone and data services, earth imaging and surveillance (Iridium, Globalstar and Orbcomm).
- GPS system uses 24 medium earth orbit (MEO) satellites – revolution in navigation. Now every car and phone has a GPS receiver.



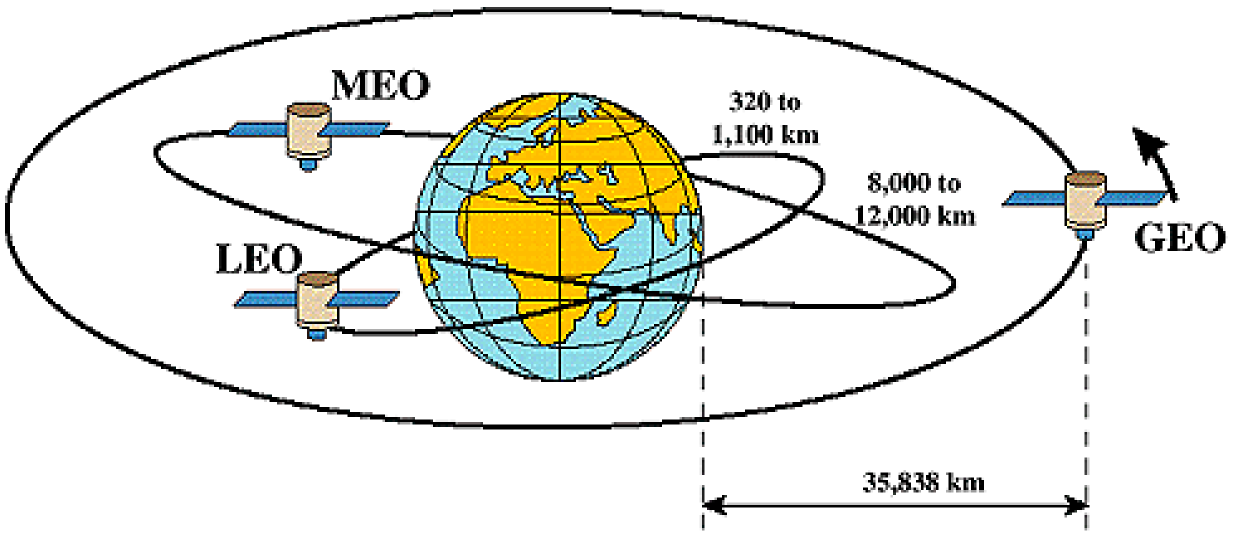
- Depending on the position of a satellite:

  - **Geosynchronous earth orbit:**
    - Satellites placed at 36000km above the Earth.
    - Orbital period of 23h 56mn, 4.1sec
    - Satellites remain in a fixed position relative to the surface.
    - Used for point-to-point communications (TV and data communications).
    - Three satellites can provide global coverage of the Earth.
    - GEO satellites typically use 30 x 46cm antennas
    - Disadvantages – long delay due to the long distance communication and low received power.
    - Propagation delay 250ms
    - Lifetime 18-20 years
    - Must carry enough station keeping fuels to maintain the orbit (otherwise will drift to north-to-south route under gravitational forces
    - Powered by solar panels – problem twice a year when earth casts a shadow over satellite (relay on back-up-batteries)
    - Now more than 200 GEO comms satellites;



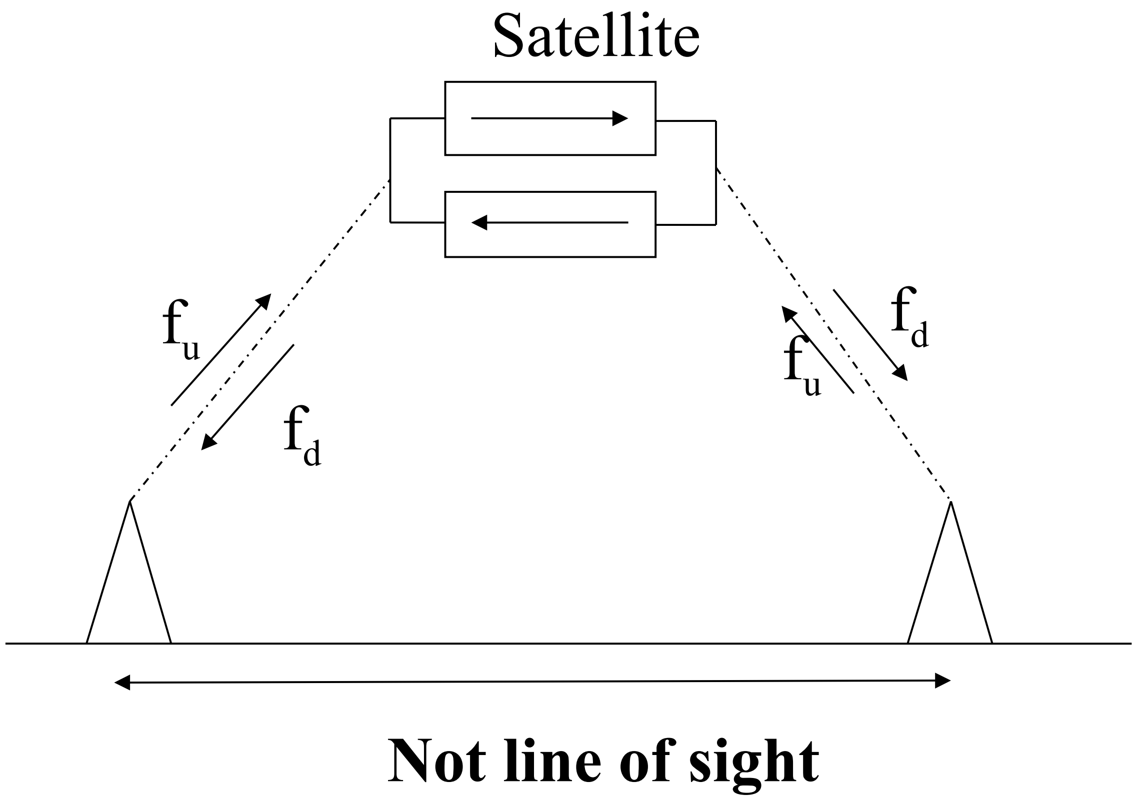


- **Low Earth Orbit (LEO) and Medium Earth Orbits (MEO)**
  - Satellite placed at 500-2000 km above the Earth
  - Cheaper to launch/build
  - Orbiting period of 100 min
  - Smaller and cheaper antennas
  - Lower attenuation (shorter path) and smaller delays
  - Effective coverage requires larger number of satellites in different orbital planes
  - Traverse the north and south poles, covering the earth surface in strips and scan the weather conditions
  - Ideal for collecting data – remote sensing (frequent communication with fixed earth stations)
  - Iridium satellite system employed 66 LEO satellites in near-polar orbits and was used to connect mobile and paging subscribers to the public telephone system (1998) .
  - Globalstar uses 48 satellites for wireless telephone and paging (2000).



- The Global Positioning System (GPS) uses 24 satellites in medium earth orbits, 20 000 km from the Earth.
- The GPS provides accurate positioning to the users. GPS receivers used in aeroplanes, boats, ships and cars. Accuracy of 1cm can be achieved.

A simple satellite link:



- The Earth station transmits the signal to the satellite at frequency f_u (uplink). This signal is received by a satellite, amplified and converted to the signal with frequency f_d which is then transmitted to the earth station (downlink).

- The uplink signal is at higher frequency because satellite antenna has limited size and at higher frequencies antenna has higher gain (for a fixed antenna size).

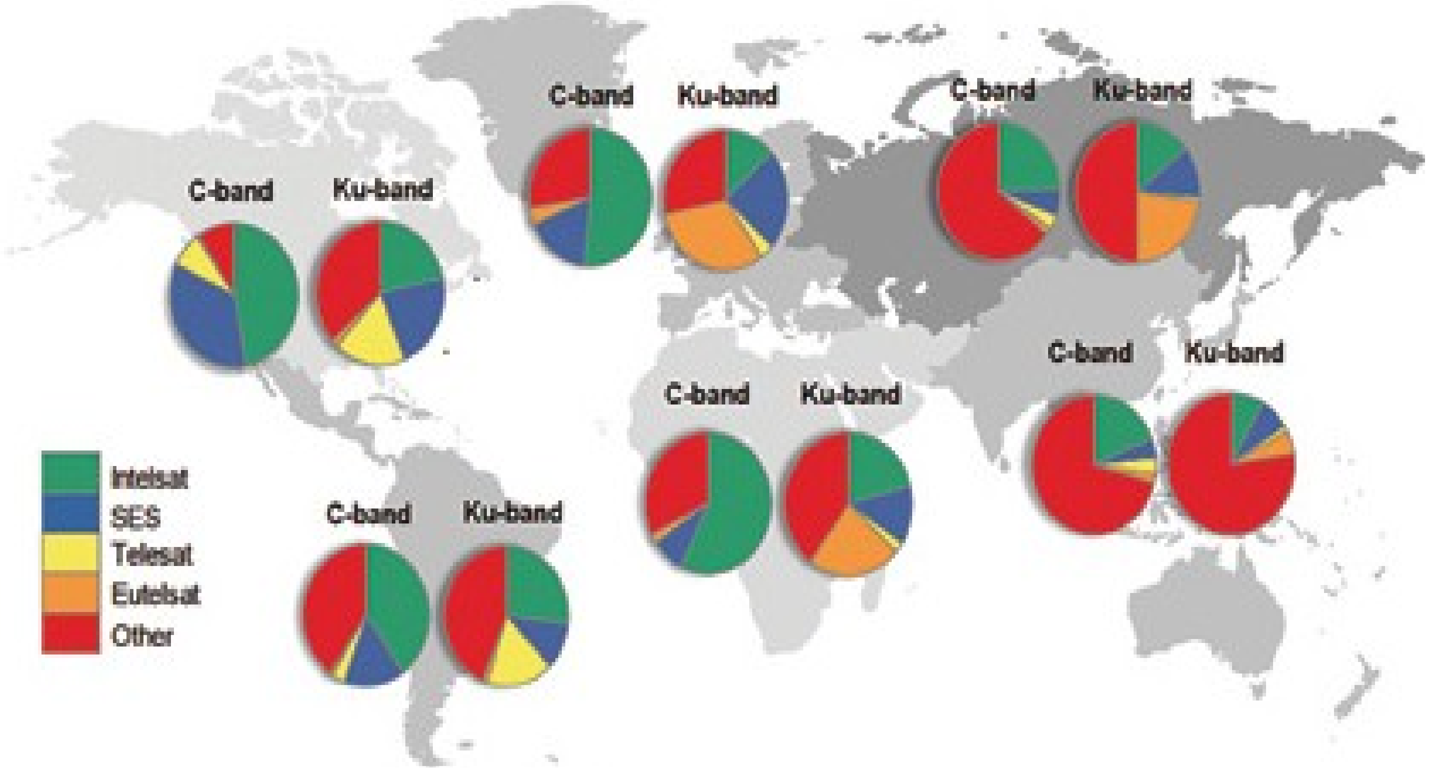
- Two different frequencies for the uplink and downlink are used to avoid interference and to enable simultaneous reception and transmission.

- Multiple access techniques are used (FDMA, TDMA of CDMA) to distribute to many users.

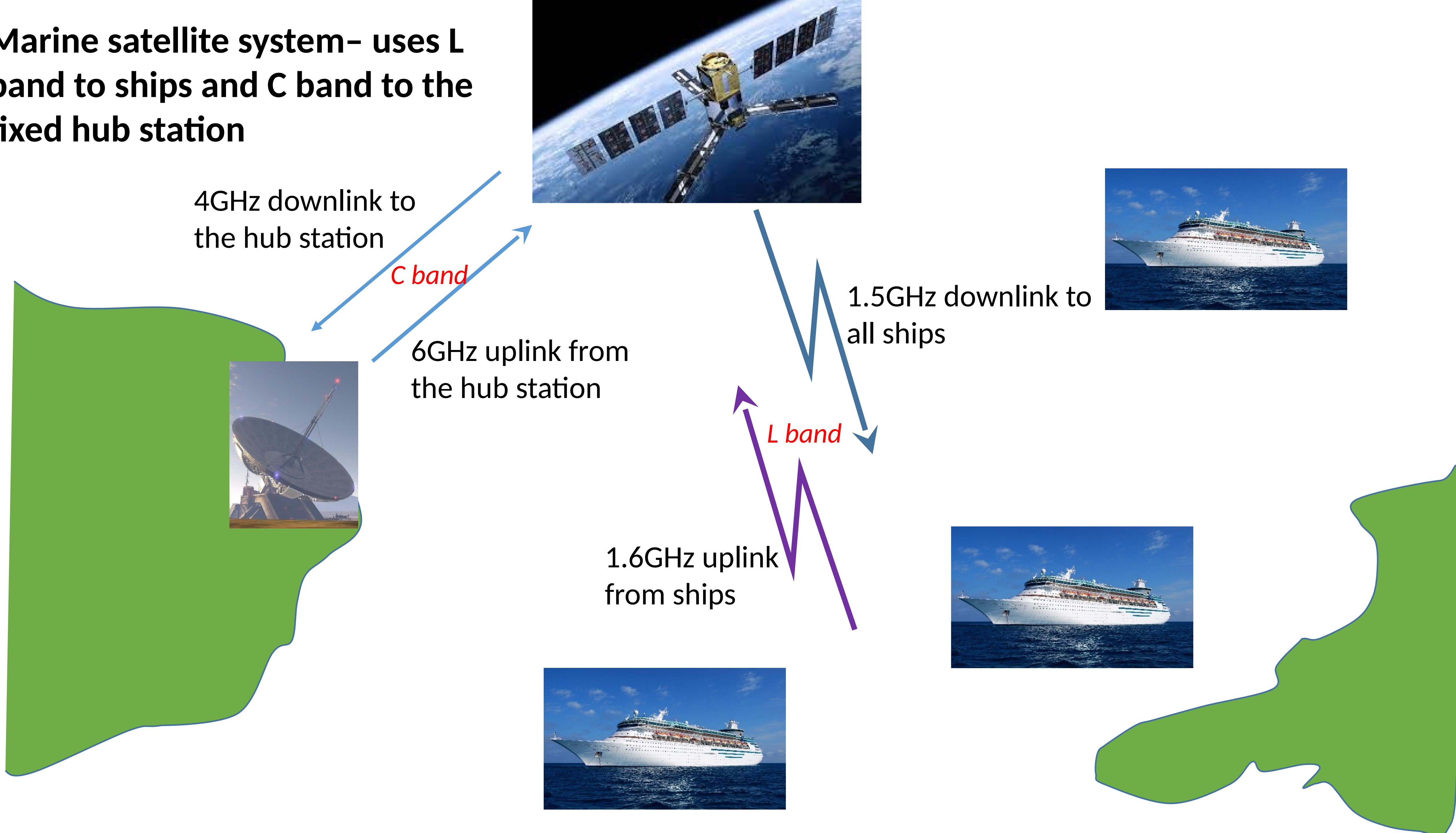
- Satellites have over time become larger and more powerful that resulted in smaller antennas on earth. (in early days earth antennas had to be 30m and modern antennas are 0.5m in diameter).
- Satellite operate in the frequency band 1-50GHz. The range of frequencies used depends on:
  - The absorption in atmosphere
  - Antenna size needed to produce a beam of certain angular spread
  - Regulations
- Early satellites used analogue signals and FM modulation; Modern satellites use digital signals for all services;
- Satellite systems operate at frequencies above 1GHz.

Frequency bands:

Band	f_u	f_d
L	1.6	1.5
C	**6**	**4**
X	8.2	7.5
Ku	**14**	**11**
Ka	30	20
Q	44	21



Marine satellite system– uses L band to ships and C band to the fixed hub station

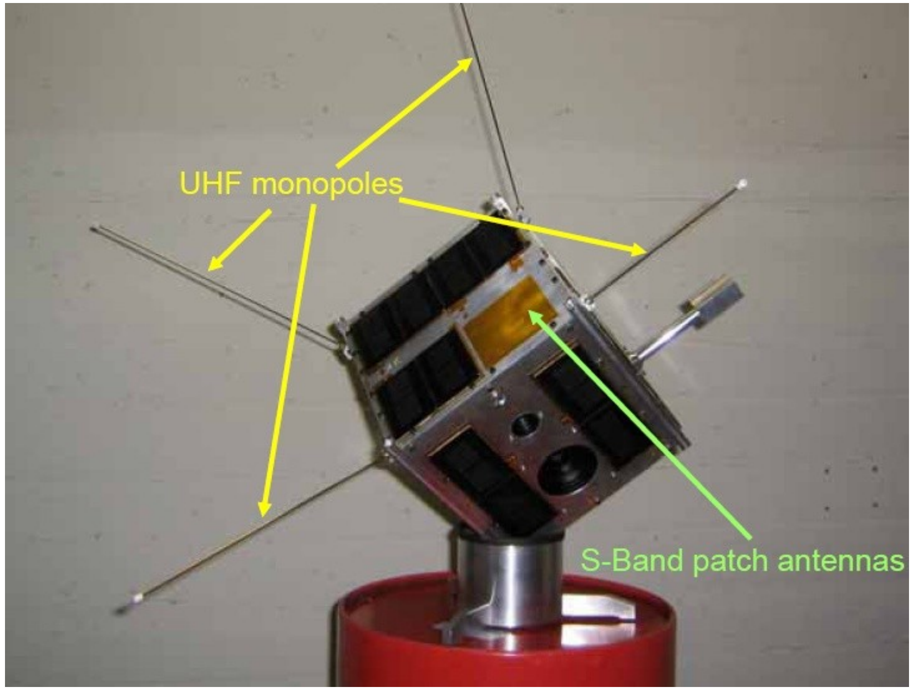


Satellite antennas

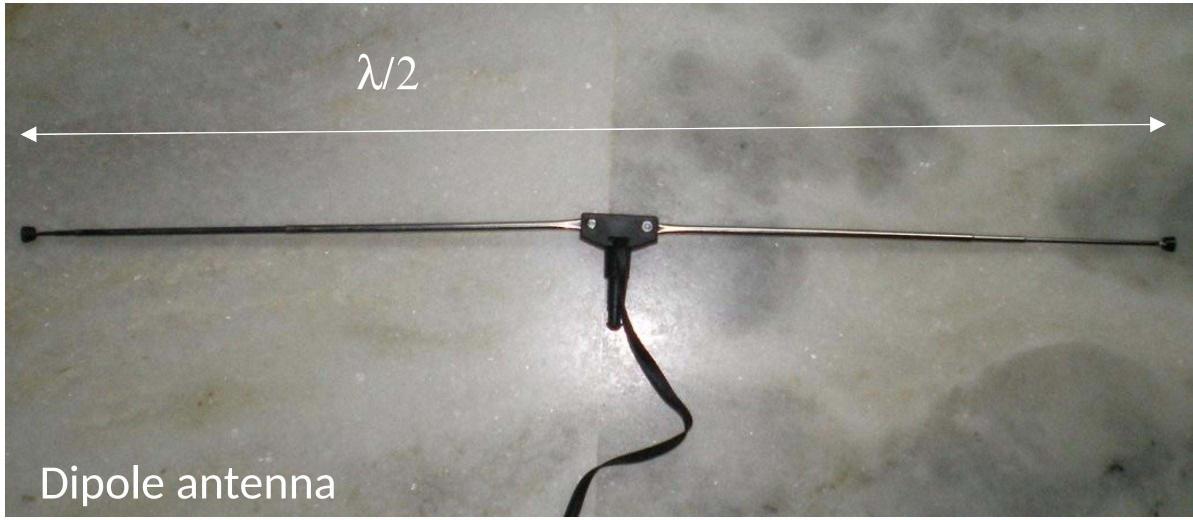
- Four main types of antennas are used on satellites:
  - Wire antennas; monopoles and dipoles
  - Horn antennas
  - Reflector antennas
  - Array antennas

- Wire antennas are used primarily for VHF and UHF bands and they are positioned so that they provide **omnidirectional** coverage. (Omnidirectional coverage provides the same coverage in all directions).
- Horns and reflector antennas are aperture antennas that launch a wave into a free space from a waveguide.
- Horn antennas are used at microwave frequencies and have relatively wide beams. Horns are also used as feeds into reflector antenna. Typically the gain is around 23 dB and beam width is less than 10^o.
- Reflector antennas are illuminated with one or more horn antennas and generate the plane wave in order to achieve maximum gain. A paraboloid for reflector shape with the feed in its focus point will provide a plane wave excitation. Typically, large paraboloid reflectors are used on earth stations.
- Phased array antennas are used on satellites to provide multiple beams.

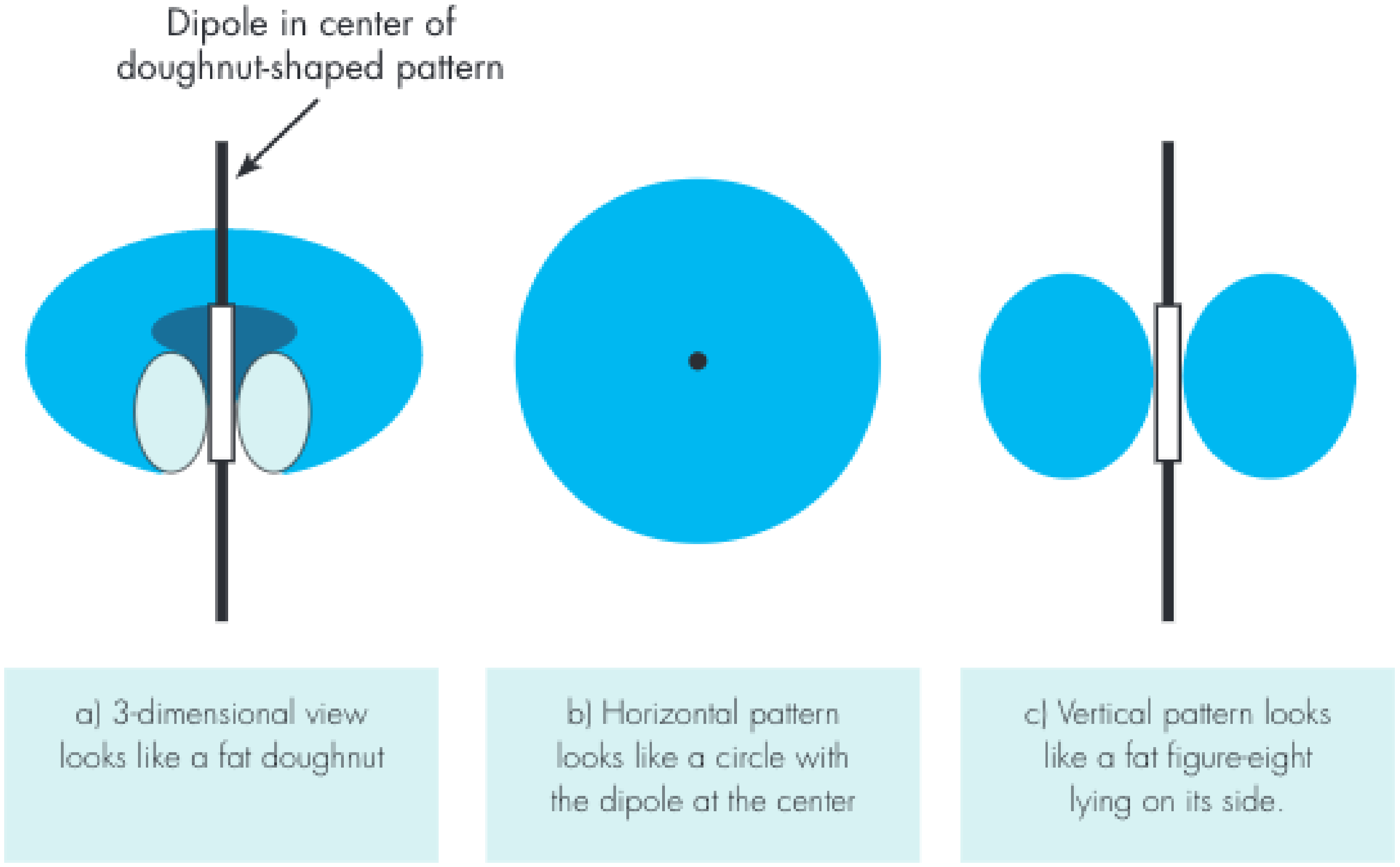
Satellite antennas – wire antennas (monopoles and diplose)



- Wire antennas are used primarily for VHF and UHF bands and they are positioned so that they provide **omnidirectional** coverage. (Omnidirectional coverage provides the same coverage in all directions).
- The length of a monopole is $\lambda/4$ where λ is the operating wavelength.
- The length of a dipole is $\lambda/2$.



Monopole and dipole antenna radiation pattern



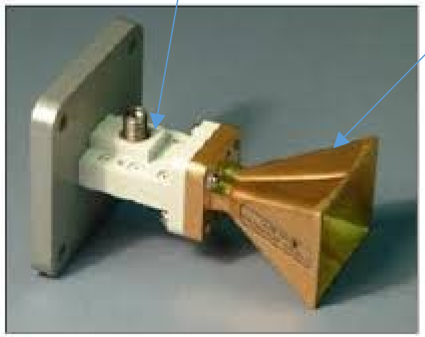
http://blog.commscopetraining.com/increase-antenna-signal-strength-with-design/

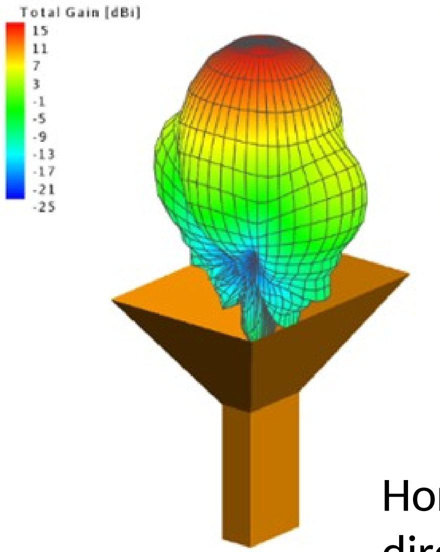
Horn antennas

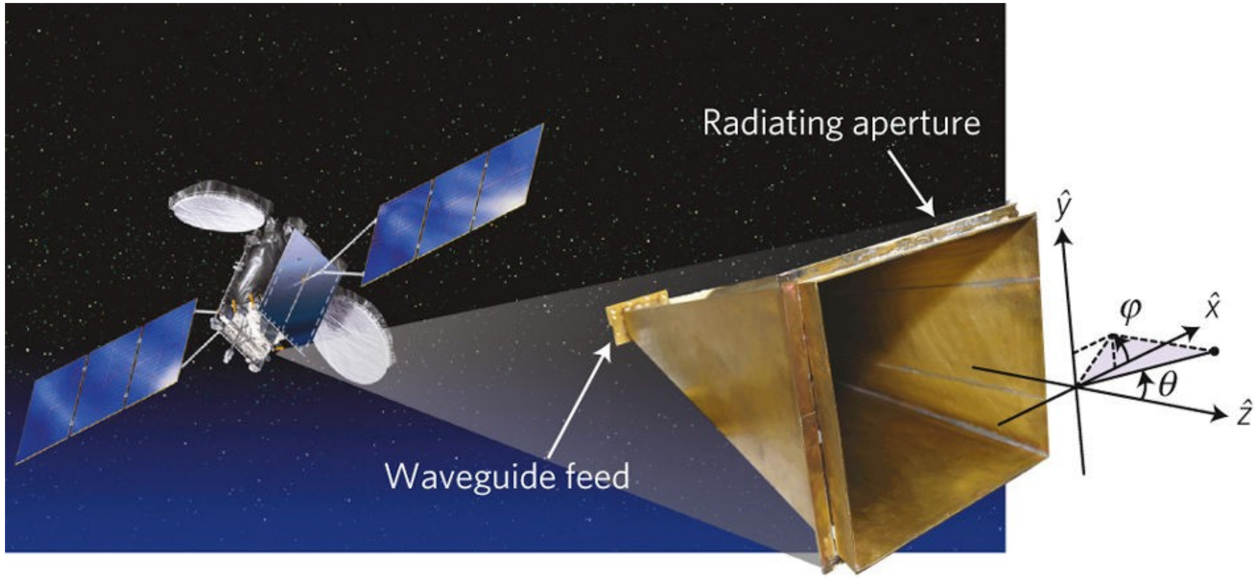
- Horns and reflector antennas are aperture antennas that launch a wave into a free space from a waveguide.
- Horn antennas are used at microwave frequencies and have relatively wide beams. Horns are also used as feeds into reflector antenna. Typically the gain is around 23 dB and beam width is less than 10°.

waveguide

Horn antenna



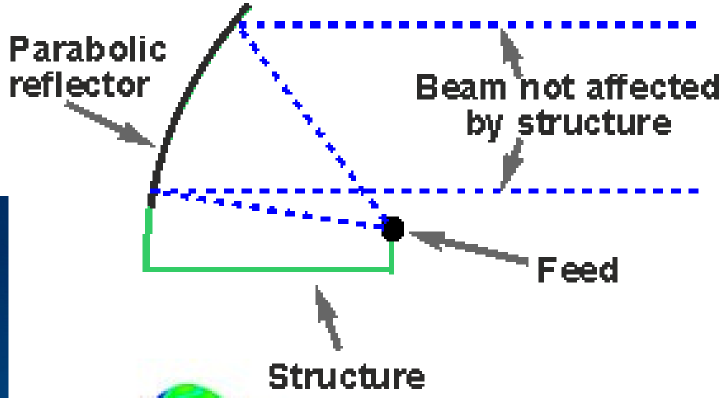


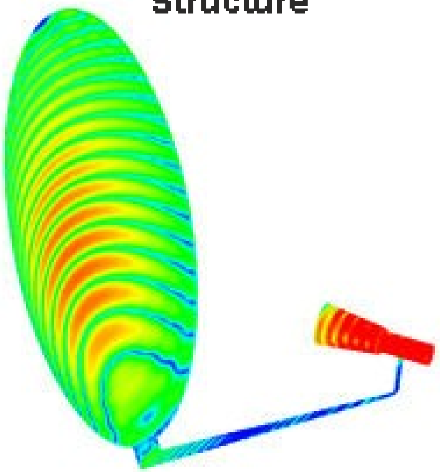


Horn antennas have a more directive radiation pattern

Reflector antennas

- Reflector antennas are illuminated with one or more horn antennas and generates the plane wave in order to achieve maximum gain. A paraboloid for reflector shape with the feed in its focus point will provide a plane wave excitation. Typically, large paraboloid reflectors are used on earth stations.

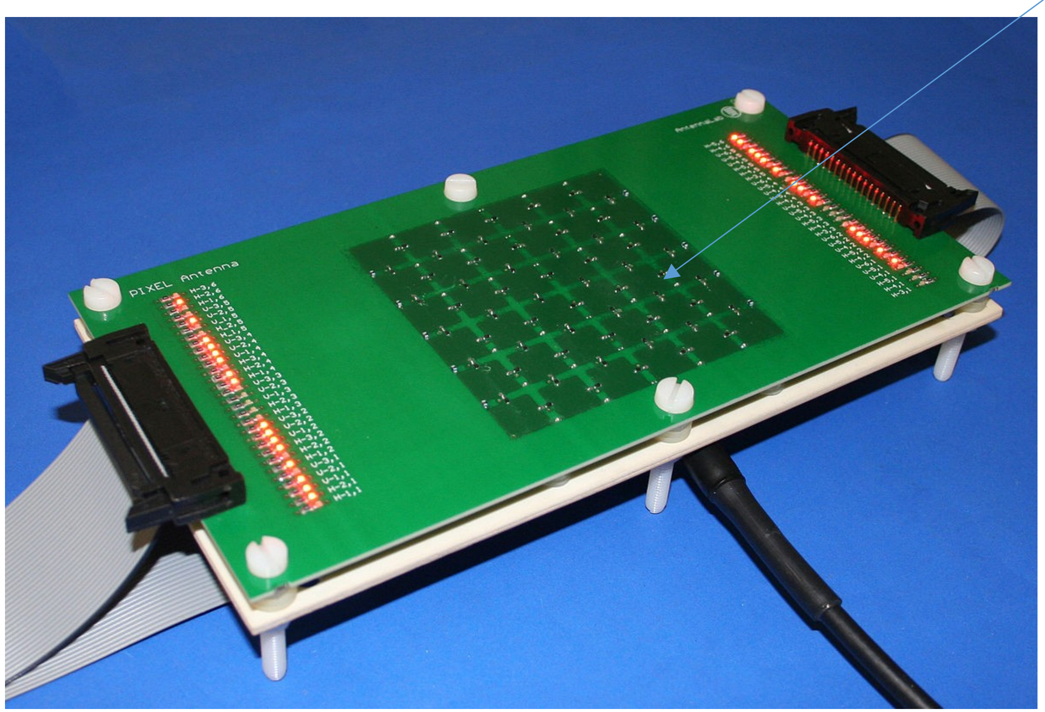


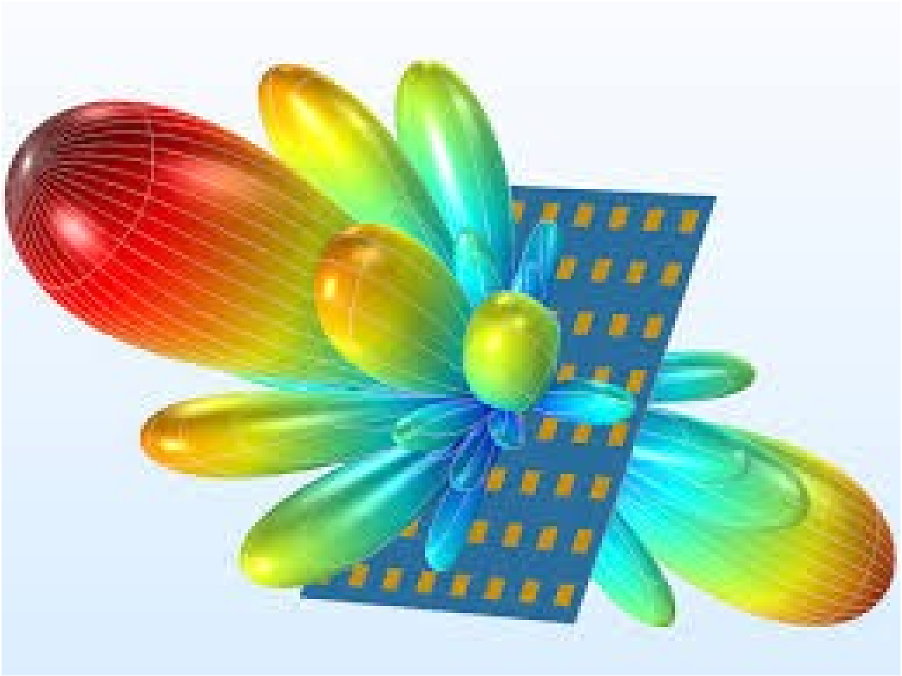


Phased array antennas

- Phased array antennas are used on satellites to provide multiple beams.
- Phased array consists of a number of antenna elements arranged in a certain geometrical pattern. Excitation of each individual antenna with an appropriate phase (and the same amplitude) provides radiation pattern with multiple beams.

Patch antenna phased array





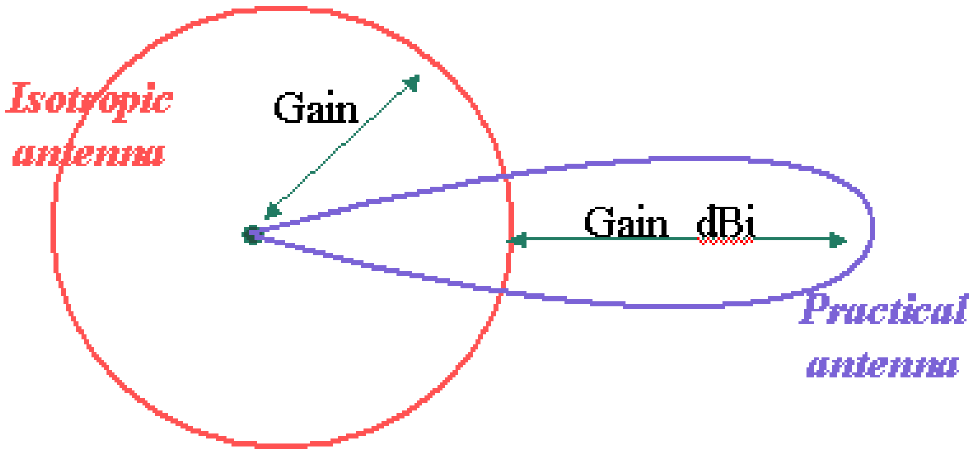
- An aperture antenna has a gain, G, given by:

$$G = \frac{4\pi}{\lambda^2} A_e = \eta_e \frac{4\pi}{\lambda^2} A \qquad Ae = \eta e A$$

- Where A_e is **effective aperture**, A is **area of antenna** in meters and $\boldsymbol{\eta_e}$ **is the aperture efficiency** of antenna. Antenna efficiency is typically 55-68% for reflector antennas; horn antennas have higher efficiencies 65-80%.

- If aperture is circular the antenna area is $\pi D^2/4$, where D is the diameter of antenna and antenna gain is:

$$G = \frac{4\pi}{\lambda^2} A_e = \frac{4\pi}{\lambda^2}\left(\eta_e \frac{\pi D^2}{4}\right) \text{¿} \, \eta_e \left(\frac{\pi D}{\lambda}\right)^2$$



- Gain of antenna can also be given in dB as

$$G_{dB} = 10\log(G)[dB]$$

In practise G is a measure of an increase in radiated power radiated by antenna over that from an isotropic point source, measured at dBi.

Example: An earth station uses an antenna of 12m diameter with an efficiency of 65% to receive a signal at 4GHz. Determine the gain of antenna in dB.

(Answer: G=164063.7 or 52.15 dB)

Satellite link – power received by the earth station

- Consider a transmitting source in free space that radiates a total power of P_t uniformly in all directions. Such source is called ***isotropic*** – and is an idealised radiator that is used to define practical antennas.
- At a distance R the power density, S, will be:

$$P_{den} = \frac{P_t}{4\pi R^2} [W / m^2]$$

- All antennas are directional and radiate more power in certain directions.
- The power density at distance R radiated from a transmitter of power P_t and gain G_t is:

$$P_{den} = \frac{P_t G_t}{4\pi R^2} \left[W / m^2 \right]$$

- The product $P_t G_t$ is called the Effective Isotopically Radiated Power or EIRP.

- If receiving antenna has a physical aperture area of A [m^2] the collected power would be:

$$P_r = P_{den} \cdot A \lfloor W \rfloor$$

- But in reality it is $P_r = P_{den} \cdot A_e \lfloor W \rfloor$
- Practical antenna will deliver less power as some of the energy will reflect away from antenna and some will be absorbed by lossy components. This reduction is described by ***effective aperture A_e***

$$A_e = \eta_A \cdot A \lfloor m^2 \rfloor$$

- And η_A is the aperture efficiency of antenna. The gain of the receiving antenna is:

$$G_r = \frac{4\pi A_e}{\lambda^2} = \eta_e \frac{4\pi}{\lambda^2} A$$

- The power received by a real antenna is

$$P_r = \frac{P_t G_t A_e}{4\pi R^2} = \frac{P_t G_t G_r}{(4\pi R / \lambda)^2} [W]$$

This is the link equation.

$$P_r = \frac{P_t G_t G_r}{(4\pi R/\lambda)^2}\left[W\right]$$

The term $(4\pi R/\lambda)^2$ is known as ***path loss*** (*L_p*) and accounts for the way energy is spread out as an electromagnetic wave in three-dimensional space. (It is not loss in the sense that power is being absorbed).

In comms system power is given in decibels and we can express link equation as:

$$P_r = EIRP + G_r - L_p\left[dBW\right]$$

$$EIRP = 10\log_{10}(P_t G_t)\left[dBW\right]$$

$$Gr = 10\,log\,10\left(Gr\right)\left[dB\right]$$

$$L_p = 10\log_{10}(4\pi R/\lambda)^2 = 20\log_{10}(4\pi R/\lambda)\left[dB\right]$$

The link equation as given above describes an idealized case where no additional losses are included. It described transmission between 2 antennas in free space.

dBW- means greater or less than 1W

A satellite link

Receiving antenna loss L_{ra}

Path loss L_p

Transmitting antenna loss L_{ta}

Atmospheric loss L_a

- All losses (atmospheric losses (L_a), transmission and receiving antenna losses due to mis-pointing, L_{ta}, L_{ra}) are included in system margin:

[dBW]

A margin of 3-5 dBs is enough to cover for changes in atmosphere and weather conditions.

Example:

A satellite at a distance of 38000 km from a point on the earth's surface radiates a power of 12W from an antenna with a gain of 17dB in the direction of the observer.

a) Find the power density at the receiving point and the power received by antenna at this point with an effective area of 10 m^2.

b) Find the power density in dBW/m^2 and received power in dBW.

Solution:

Convert the antenna gain from dB:

a)

$$G_{t,dB} = 10\log G_t \Rightarrow G_t = 10^{(G_{t,dB}/10)} = 10^{17/10} = 10^{1.7} = 50.12$$

$$P_{den} = \frac{P_t G_t}{4\pi R^2} = \frac{12 \cdot 50.12}{4 \cdot 3.14 \cdot (38000 \cdot 10^3)^2} = 3.3 \cdot 10^{-14}\left[W/m^2\right]$$

$$P_r = P_{den} \cdot A_e = 3.3 \cdot 10^{-13}[W]$$

b)

$$P_{den,dB} = 10\log P_{den} = -134.5 dBW/m^2$$

Alternatively the power density in dB can be calculated as:

$$P_{den} = 10\log P_t + G_{t,dB} + 10\log\left(\frac{1}{4\pi R^2}\right) = 10.8 + 17 - 162.3 = -134.5 dBW/m^2$$

$$P_{r,dB} = 10\log P_r = -124.81[dBW]$$

Example:
A satellite at a distance of 38000 km from a point on the earth's surface radiates a power of 12W from an antenna with a gain of 17dB in the direction of the observer. The satellite link operates at 11GHz.
Find the power in dBW received by an antenna with a gain of 52dB.

Solution:

$$P_r = \frac{P_t G_t G_r}{(4\pi R/\lambda)^2}[W]$$

$$P_{r,dB} = 10\log P_t + G_{t,dB} + G_{r,dB} - L_p = 10\log P_t + G_{t,dB} + G_{r,dB} - 20\log\left(\frac{4\pi R}{\lambda}\right)$$

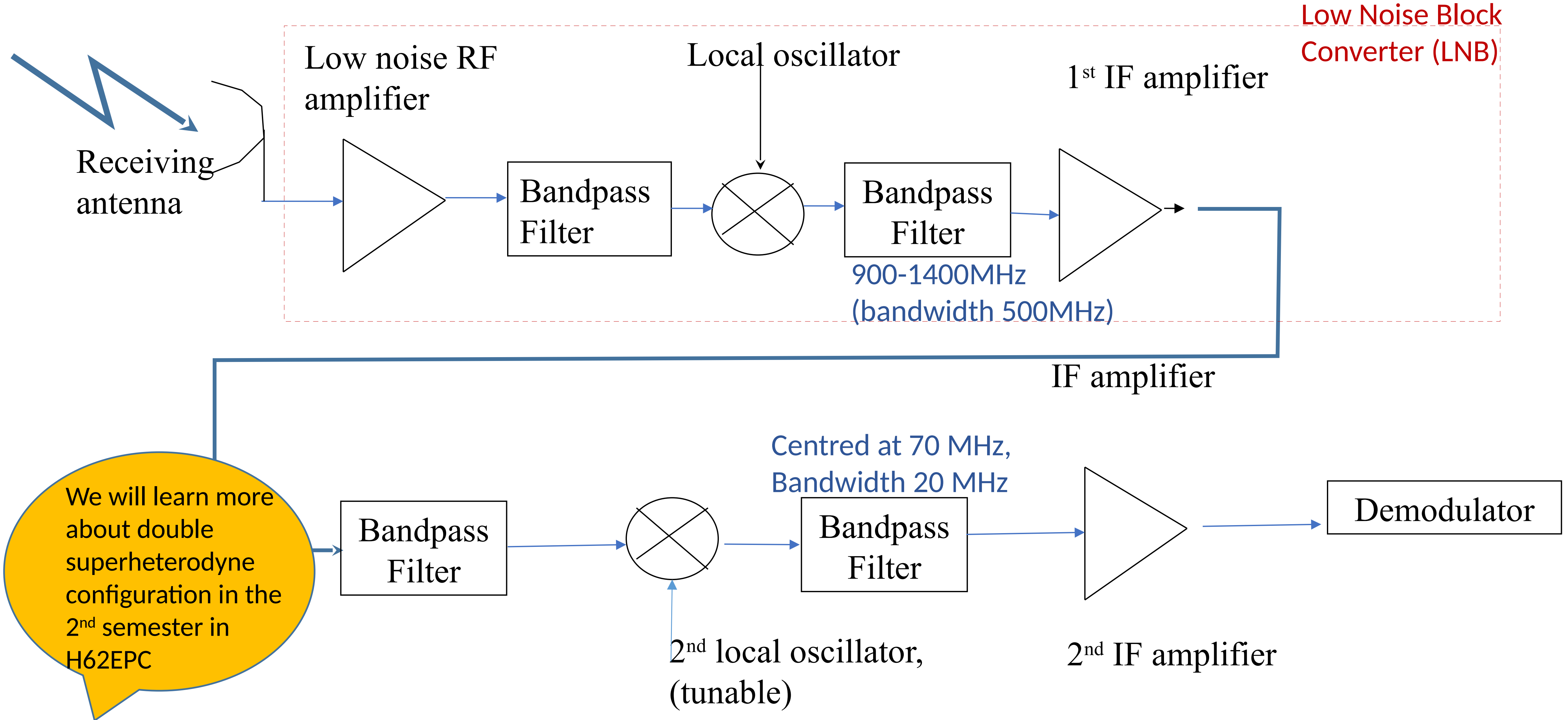
$$\lambda = \frac{c}{f} = \frac{3\cdot 10^8}{11\cdot 10^9} = 0.027m$$

$$P_{r,dB} = 10\log P_t + G_{t,dB} + G_{t,dB} - L_p = 10\log P_t + G_{t,dB} + G_{t,dB} - 20\log\left(\frac{4\pi 38000\cdot 10^3}{0.027}\right) =$$

$$= 10.8 + 17 + 52 - 204.9 = -125.1dBW$$

Earth station receiver – double superheterodyne configuration

- Before we account for the losses in the receiver lets have a look at the components of the earth station receiver.



Noise Model of a Receiver

- Noise temperature is a concept we use to determine how much thermal noise is generated by an active and passive device in a receiving system.
- At microwave frequencies a black body with a physical temperature of T generates electrical noise over a bandwidth as:

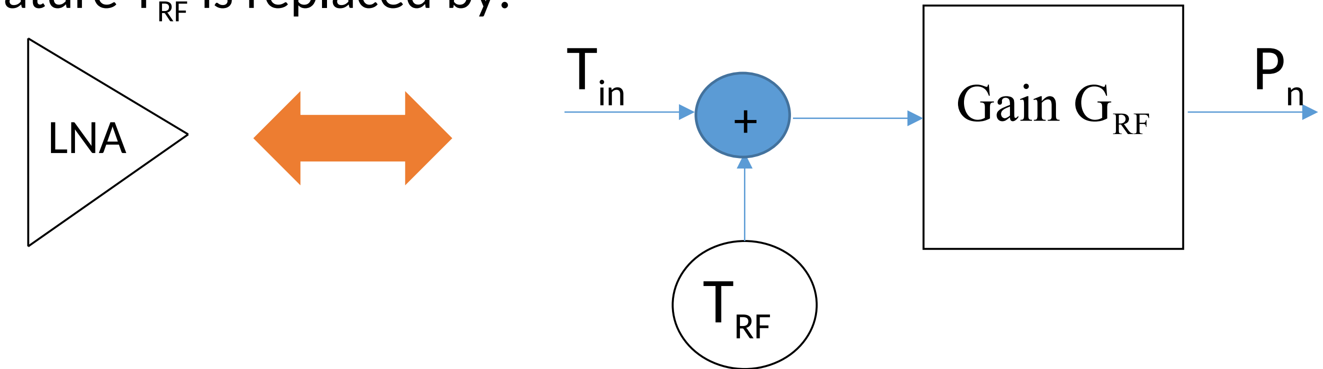
$$P_n = kTB$$

k = Boltzmann's constant =1.3910^{-23}J/K

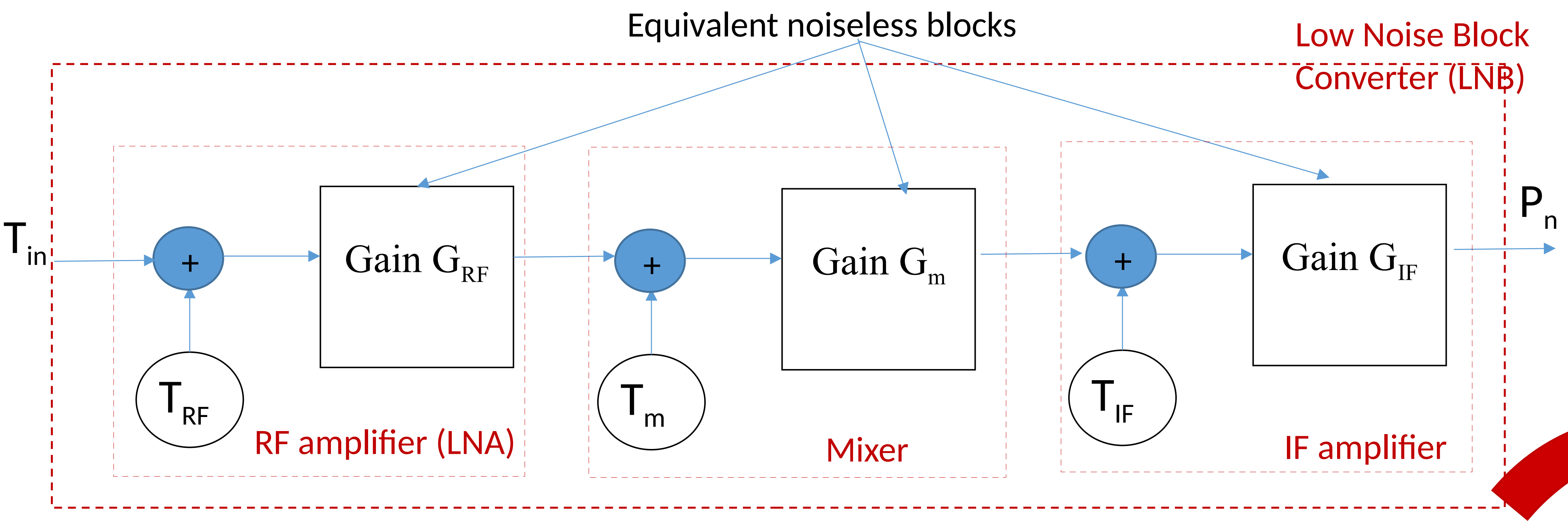
T = physical temperature of source in Kelvins

B = noise bandwidth in which noise power is measured in Hz.

- The noise produced by a component in a receiver is described by equating a component to a black body radiator with ***an equivalent noise temperature T_n*** in Kelvins. A device with a noise temperature of T_n produces at the output the same noise as a black body at a temperature T_n , ***followed by a noiseless amplifier*** with the same gain as the actual device.
- For example LNA of gain G_{RF} and noise temperature T_{RF} is replaced by:



Noise model of a receiver



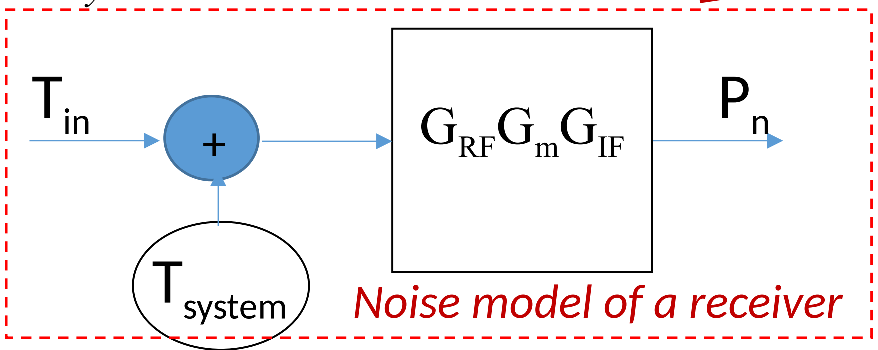
The total noise power is:

$$P_n = G_{RF} G_m G_{IF} k B_n (T_{in} + T_{RF}) + G_m G_{IF} k T_m B_n + G_{IF} k T_{IF} B_n =$$

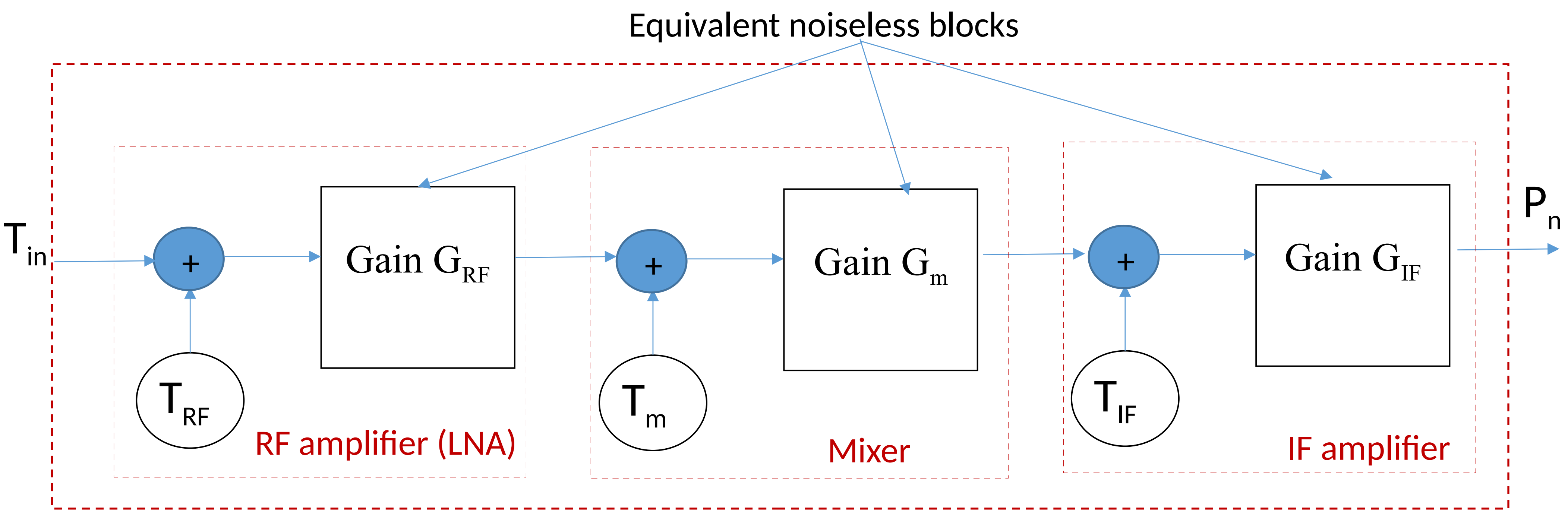
$$G_{RF} G_m G_{IF} k B_n \left[T_{RF} + T_{in} + T_m / G_{RF} + T_{IF} / (G_{RF} G_m) \right] = G_{RF} G_m G_{IF} k T_{system} B_n$$

The equivalent noise source of a receiver has system noise temperature T_{system}:

$$T_{system} = \left[T_{RF} + T_{in} + T_m / G_{RF} + T_{IF} / (G_{RF} G_m) \right]$$



Noise model of a receiver



The equivalent noise source of a receiver has system noise temperature T_{system}:

$$T_{system} = \left[T_{RF} + T_{in} + T_m / G_{RF} + T_{IF} / (G_{RF} G_m) \right]$$

This is a very important result – it shows that the noise temperature of the 2nd (mixer) and 3rd stage (IF amplifier) is divided by the power gain of the first stage (LNA) when referred to the input. Therefore, to keep the overall system noise down the first stage should have the highest power (usually the LNA) as well as low noise temperature.

Example:

A 4GHz receiver has following gains and noise temperatures:

$$T_{in} = 25K, T_{RF} = 52K, T_{IF} = 900K, T_m = 450K, G_{RF} = 22dB, G_{IF} = 29dB$$

a) Calculate the system noise temperature assuming that the mixer has a gain of Gm=0dB.

b) Re-calculate the system noise temperature assuming that the mixer has 10 dB loss.

c) How can the noise temperature of the receiver be minimised when the mixer has the loss of 10dB.

Solution:

a) Convert gain from dB to linear values: $G_{RF}=10^{2.2}=158$, $G_m=1$, $G_{IF}=794$;

$$T_{system} = \left[T_{RF} + T_{in} + T_m / G_{RF} + T_{IF} / \left(G_{RF} G_m\right)\right] = 85.5K$$

b) Loss can be treated as gain where linear gain is < 1. If Mixer has 10 dB loss then linear gain is $G_m=0.1$.

$$T_{system} = \left[T_{RF} + T_{in} + T_m / 158 + T_{IF} / \left(158 \cdot 0.1\right)\right] = 136.7K$$

c) By increasing the gain of RF amplifier, G_{RF}.

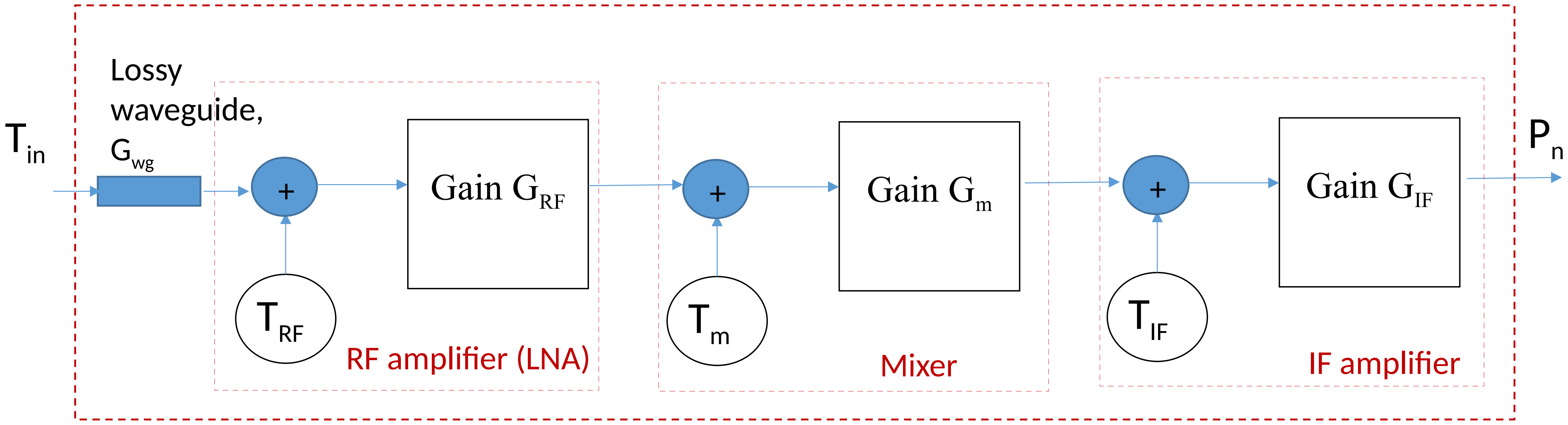
Example:

A 4GHz receiver has following gains and noise temperatures:

$$T_{in} = 25K, T_{RF} = 52K, T_{IF} = 900K, T_m = 450K, G_{RF} = 50dB, G_{IF} = 29dB, G_m = -10dB$$

A section of lossy waveguide with an attenuation of 2dB is inserted between the antenna and the RF amplifier. Find the noise temperature for a waveguide temperature of 300 K.

Solution:



Linear loss of the waveguide is:

$L_{wg}=G_{wg}=10^{-2db/10}=0.63.$

Noise temperature of the lossy component:

$$T_{wg} = T_{wg}\left[1 - G_{wg}\right] = 300\left[1 - 0.63\right] = 110.7K$$

$$T_{in} = 0.63 \cdot 25 = 15.7K$$

The waveguide attenuates the input noise from the antenna

$$T_{system} = \left[T_{in} + T_{RF} + T_{wg} + T_m / G_{RF} + T_{IF} / \left(G_{RF} G_m\right)\right]$$

To conclude

- Friis equation can be used to define satellite link – we added atmospheric loss and antenna pointing errors to the equation
- Received powers are very low so low noise receiver is required for maximum signal to noise ratio
- To keep the overall system noise down the first stage of the receiver (RF amplifier or LNA) should have the highest power as well as low noise temperature.

Overview

- Satellite downlink design
  - Introduce new parameters C/N ratio, Noise Figure, S/N, BER
- Design of a downlink: link budget

Noise Figure, Noise Temperature and C/N ratio

- Noise figure is used to define noise generated by device, and is defined as a ratio of signal to noise at the input and signal to noise at the output of the device:

$$NF = \frac{(S/N)_{in}}{(S/N)_{out}}$$

- The NF can be converted to noise temperature is: $T = T_0(NF - 1)$
- Where T_0 is the reference temperature used to calculate the standard noise figure – usually 290K.
- Carrier to Noise ratio, C/N, is:

$$\left(\frac{C}{N}\right) = \left[\frac{P_t G_t G_r}{k T_s B_n}\right]\left[\frac{\lambda}{4\pi R}\right]^2 = \left[\frac{P_t G_t}{k B_n}\right]\left[\frac{\lambda}{4\pi R}\right]^2\left[\frac{G_r}{T_s}\right]$$

- Terms in square brackets are constant for a given satellite system. C/N is proportional to G_r/T_s; Increasing G_r/T_s also increases C/N.
- G/T ratio for satellite may be quoted as negative G/T which is below 0 dB/K. That means that numerical value of G is smaller than numerical value of T.

Example:

An earth station antenna has a diameter of 30m and efficiency of 68% and is used to receive a signal at 4.15GHz. At this frequency the system noise temperature is 79K when the antenna points at the satellite at an elevation angle of 28deg.

a)What is the earth station G/T ratio under these conditions?

b) If heavy rain causes sky temperature to increase so that the system noise temperature rises to 88K what is the new G/T value?

Solution:

a) Calculate gain of the receive antenna:

$$G_r = \eta \frac{4\pi}{\lambda^2} A = \eta \frac{4\pi}{\lambda} \frac{D^2 \pi}{4} = \eta \left(\frac{\pi D}{\lambda} \right)^2 0.68 \frac{4 \cdot 30}{(3 \cdot 10^8 / 4.15 \cdot 10^9)} = 1.16 \cdot 10^6$$

$$G_{r,dB} = 10 \log\left(1.16 \cdot 10^6\right) = 60.6 dB$$

Convert T in dBK as T=10 log(79)=19 dBK

Calculate G/T = G-T[db]=60.6-19=41.6dB/K

b) G/T=60.6-10log(88)=60.6-19.4=41.2dB/K

Satellite link design

- The cost to build and launch a GEO satellite is ~$25 000 per kg.
- Weight is the most critical factor in satellite design as the cost must be recovered over a lifetime (~15years) of selling comms services.
- GEO satellites use solar panels and antennas and as antenna reflectors are not foldable they cannot be greater than the spacecraft which is of 3.5 m in diameter. This means that diameter of antenna is limited to 3.5 m and presents one of the limiting factors in the performance of comms system. (remember that effective area of antenna is proportional to its surface and it is also proportional to the gain of antenna).
- The weight of the satellite is driven by the number of transponders and the fuel tank. Increasing the total power of the transponders requires larger solar cells that in turn increase the total weight.
- Three other important factors in link design are:
  - The choice of frequency band – most popular are C and Ku band
  - Atmospheric effects – little attenuation at 4GHz and 6 GHz but more severe as frequencies are increased (above 10GHz)
  - Multiple access technique

Performance measures: BER, S/N and C/N

- All communication links have to meet certain performance objectives **Bit Error Rate (BER)** (for digital links) or **Signal to Noise ratio** (S/N) for analogue links, measured at the baseband channel (ie where the information is generated or received). ***As such BER or S/N defines the quality of the signal generated or received by the user.***
- BER or S/N are determined by **Carrier to Noise ratio (C/N)** at the input to demodulator in the receiver.
- C/N is calculated at the input to receiver, ie. at the output terminals of the receiving antenna.
- In most satellite systems C/N >6dB.
- Digital links with C/N<10dB must *use error correction techniques* to improve the BER delivered to the user.
- RF noise generated by receiver are combined into equivalent noise power at the input of a receiver and a noiseless receiver model is used. In a noiseless receiver C/N is constant at all points in the RF and IF chain and C/N is the same at the receiver and demodulator.
- Satellite link has 2 paths – uplink and downlink – the overall C/N has to be satisfied for both links for a specified percentage of time.

Design of downlink – link budget

- The design of any satellite comms system is based on 2 objectives: meeting a minimum C/N ratio and carrying maximum revenue at minimum cost;
- All satellite links are affected by rain attenuation. In the band 6/4 GHz the effect of the rain is small but this increases in 15/11 GHz band and 30/20 GHz band.
- Links are designed to have reliabilities of 99.5%-99.99% averaged over a year.
- C-band has reliability of 99.99% which means that in 0.01% is suffers outages (52 min over a year).
- In Ka band links outage times are 0.1-0.5% of a year (8-40h).
- Link budget is a tabular method or evaluating received power and noise power in the comms link. Units are decibels so that all signals and noise powers are calculated using addition and subtraction.
- We will look at the components that make link budget for C-band GEO satellite in clear air and in rain. (Example taken from Satellite Communications, Timothy Prat et all, 2nd edition, John Wiley and Sons, 2003)

C-band GEO Satellite Link Budget in Clear Air – MAIN COMPONENTS

- C-band satellite parameters – this outlines all parameters of the satellite, antenna gain, transmitted power, losses etc. (GIVEN PARAMETERS)
- Signal – type of the signal (analog or digital) and bandwidth (GIVEN PARAMETERS)
- Receiving C-band earth station – all parameters at the earth station, bandwidth, losses, antenna gain, etc. (GIVEN PARAMETERS)
- Downlink power budget – outlines all gains and losses in the link, including free space loss, atmospheric loss, antenna gains, transponder power, etc
- Downlink noise budget in clear air – calculates receiver noise power for clear air conditions

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Calculate $(C/N)_{down}$ – overall C/N calculated from the table above.

C-band GEO Satellite Link Budget in Clear Air

- C-band satellite parameters (given)
  - Transponder output power 20W
  - Antenna gain 20dB
  - Transponder bandwidth 36MHz
  - Downlink frequency band (3.7-4.2)GHz
- Signal
- Receiving C-band earth station
- Downlink power budget
- Downlink noise budget in clear air

Calculate $(C/N)_{down}$

C-band GEO Satellite Link Budget in Clear Air

- C-band satellite parameters
  - Transponder output power 20W
  - Antenna gain 20dB
  - Transponder bandwidth 36MHz
  - Downlink frequency band (3.7-4.2)GHz
- Signal (given)
  - FM-TV signal bandwidth 30MHz
  - Minimum permitted overall C/N in receiver 9.5dB
- Receiving C-band earth station
- Downlink power budget
- Downlink noise budget in clear air

Calculate $(C/N)_{down}$

C-band GEO Satellite Link Budget in Clear Air

- C-band satellite parameters
  - Transponder output power 20W
  - Antenna gain 20dB
  - Transponder bandwidth 36MHz
  - Downlink frequency band (3.7-4.2)GHz
- Signal
  - FM-TV signal bandwidth 30MHz
  - Minimum permitted overall C/N at the receiver 9.5dB
- Receiving C-band earth station
  - Downlink frequency 4GHz
  - Antenna gain 49.7dB – sometimes you may be required to find this parameter based on antenna efficiency and total antenna area)
  - Receiver IF bandwidth 27MHz
  - Receiving system noise temperature 75K
- Downlink power budget
- Downlink noise budget in clear air

Calculate $(C/N)_{down}$

C-band GEO Satellite Link Budget in Clear Air

- C-band satellite parameters
- Signal
- Receiving C-band earth station
- Downlink power budget
  - Pt- satellite transponder output power (20W) 13.0dBW
  - Transponder output backoff (loss) -2dB
  - G_t = Satellite antenna gain 20dB
  - G_r = Earth station antenna gain 49.7dB
  - L_p = Free space path loss at 4GHz -196.5dB calculated using $L_p = 20\log_{10}(4\pi R/\lambda)\lfloor dB \rfloor$
  - L_{ant} = Satellite antenna loss -3dB
  - L_a=Clear air atmospheric loss -0.2dB
  - Other losses -0.5dBN

  - P_r = Received power at the earth station = -119.5dBW
- Downlink noise budget in clear air

Calculate (C/N)

C-band GEO Satellite Link Budget in Clear Air

- C-band satellite parameters
- Signal
- Receiving C-band earth station
- Downlink power budget
- Downlink noise budget in clear air
  - Boltzmann constant -228.6dBW/K/Hz – Boltzmann constant in dBs!
  - System noise temperature , 75K 18.8dBK
  - Noise bandwidth 27 MHz 74.3dBHz

  Receiver noise power = -135.5dBW = k+T+N [dBW]

Calculate $(C/N)_{down}$

C-band GEO Satellite Link Budget in Clear Air

- C-band satellite parameters
- Signal
- Receiving C-band earth station
- Downlink power budget

  P_r = Received power at the earth station = -119.5dBW
- Downlink noise budget in clear air

  N= Receiver noise power = -135.5dBW

$$(C/N)_{down} = Pr - N = 16dB$$

C-band GEO Satellite Link Budget in rain

- C-band satellite parameters
- Signal
- Receiving C-band earth station
- Downlink power budget

P_r = Received power at the earth station in clear air = -119.5dBW

L_{rain} = Rain attenuation -1dB

P_{r_rain} = Received power at the earth station in rain = P_r-L_{rain}= -120.5dBW

N_{ca} = Receiver noise power in clear air -135.5dBW

Δ_{rain} = Increase in noise temperature due to rain 2.3dB

N_{rain} = Receiver noise power in rain -133.2dBW

$$(C/N)_{down} = P_{r\_rain} - N_{rain} = 12.7\text{dB}$$

Overview

- Satellite uplink design

Uplink design

- Easier to do as much higher power transmitters can be used at earth stations than on a satellite.
- But not all earths stations can use high power: satellite telephone handsets are transmitting at 1W , VSAT systems at 5W. In mobile systems uplink is the link with lowest C/N ratio.
- Earth station power is set by the power level required at the transponder. At C band typical uplink earth station transmits 100W with a 9 m antenna and gives the power density at the satellite of -100 dBW.
- In the uplink analysis a transponder C/N ratio is specified, measured in the noise bandwidth Bn (bandwidth of the bandpass filter at the IF stage of the earth station receiver for which the uplink signal is intended).
- The noise power at the transponder input is

$$N_{tr} = k + T_{tr} + B_n \ [dbW]$$

- The power received at the input of the transponder is (L_{up} is uplink loss other than path loss L_p)

$$P_r = P_t + G_t + G_r - L_p - L_{up} \ [dbW]$$

- Uplink C/N is then:

$$(C/N)_{up,dB} = P_r - N_{tr} \ [dBW]$$

- The power of the earth transmitter is found from the C/N equation for uplink:

$$\left(\frac{C}{N}\right)_{up} = \left[\frac{P_t G_t G_r}{kT_s B_n}\right]\left[\frac{\lambda}{4\pi R}\right]^2 = \left[\frac{P_t G_t}{kB_n}\right]\left[\frac{\lambda}{4\pi R}\right]^2\left[\frac{G_r}{T_s}\right]$$

- The downlink and uplink are at a different frequency. The path loss can be scaled as

$$A_{up} = A_{down} \cdot \left(\frac{f_{up}}{f_{down}}\right)^a$$

where 2.0<*a*<2.4

Example:

- A transponder of a Ku-band satellite has a linear gain of 127dB. The satellite's 14 GHz receiving antenna has a gain of 26dB on axis and the beam covers western Europe.

Calculate the **input power of an uplink transmitter** that gives an output power of 1W from the satellite transponder at a frequency 14.45GHz when the earth station antenna has a gain of 50dB and there is a 1.5dB loss in the waveguide run between the transmitter and antenna. Assume that the atmosphere introduces a loss of 0.5dB under clear sky conditions and that the earth station is located on the -2 dB contour of the satellite's receiving antenna.

If rain in the path causes attenuation of 7dB for 0.01% of the year what output power is required for the transmitter to guarantee that a 1 W output can be obtained from the satellite transponder for 99.99 % of the year if uplink power control is used? Assume a path length of 38 500 km.

Solution:

Power at the output of transponder is the power at the input Plus gain of the transponder.

$$P_{out} = P_{in} + G_r = 10\log(1) = 0dBW$$

$$P_{in} = P_{out} - G_r = 0 - 127dB = -127\,[dBW]$$

The transmitter power is given from the uplink equation:

$$P_{in} = P_r = P_t + G_t + G_r - L_p - L_{wg} - L_{at} - L_{pl}\,[dbW]$$

$$P_t = P_{in} - G_t - G_r + L_p + L_{wg} + L_{at} + L_{pl} = -127 - 26 - 50 + 207 + 1.5 + 0.5 + 2 = 8\,[dbW]$$

In the case of rain the power needs to be increased by 7dBW $\quad P_{t\_rain} = P_t + 7 = 15\,[dBW]$

Overall C/N ratio

- Overall C/N ration is measured at the earth station at the output of the IF amplifier:

$$\left(\frac{C}{N}\right)_0 = \left[\frac{1}{1/(C/N)_{up} + 1/(C/N)_{down}}\right]$$

- We also must include any interference either in satellite receiver or the earth station receiver ie. intermodulation products (defined by C/I carrier-to-interference), interference from adjacent satellites whenever a small receiver antenna is used as in VSATs (very small aperture terminals) and DBS-TV receivers.

Example

- Thermal noise in an earth station receiver results in a $(C/N)_{down}$ of 20dB. A signal is received from a bent pipe in transponder with a carrier to noise ratio results in $(C/N)_{up}$ of 20 dB.

a) What is the value of overall $(C/N)_0$ at the earth station?

b) If the transponder introduces intermodulation products with C/I ratio of 24dB what is the overall $(C/N)_0$ ratio at the receive earth station.

Solution:

For this calculation C/N ratio have to be given on a linear scale.

c) $(C/N)_{dB}=20dB \Rightarrow (C/N)=10^2=100$

$$\left(\frac{C}{N}\right)_0 = \left[\frac{1}{1/(C/N)_{up} + 1/(C/N)_{down}}\right] = \left[\frac{1}{1/100 + 1/100}\right] = 50,\ or\ 16.9dB$$

d) $(C/N)_{IM,dB}=24 \Rightarrow (C/N)_{IM}=251.,\ 1/(C/N)_{IM}=0.004.$

$$\left(\frac{C}{N}\right)_0 = \left[\frac{1}{1/(C/N)_{up} + 1/(C/N)_{down} + 1/(C/N)_{IM}}\right] = \left[\frac{1}{0.01 + 0.01 + 0.004}\right] = 41.7\ or\ 16.2dB$$

Example:

- Design a transmitting earth station to a provide clear C/N of 30dB in a Ku band transponder on a geostationary satellite at a frequency of 14.15 GHz. Satellite antenna gain is 31dB. Use an uplink antenna with a diameter of 5m and an aperture efficiency of 64% and find an uplink transmitter power required to achieve the required C/N. The uplink station is located at a -2dB contour of the satellite footprint. Allow 1dB losses on the uplink for miscellaneous and clear air losses. Assume distance to satellite is 38 500 km. Transponder Ku band bandwidth is 54MHz and receive system noise temperature is 500K.

Solution

- At the satellite:

$$(C/N)_{up,dB} = P_r - N_r\ [dBW] \quad (1)$$

$$N_{tr}\ [dBW] = 10\log(k) + 10\log(B_n) + 10\log(T_s) \quad (2)$$

$$P_{r,dB}[dBW] = P_t + G_t + G_r - L_{path} - L_{ant} - L_{misc} = P_t + G_t + 31 - 20\log\left(\frac{4\pi 38500 \cdot 10^3}{0.0212}\right) - 2 - 1$$

$$G_{t,dB} = 10\log(\eta_e \frac{4\pi}{\lambda^2} A) = 10\log(\eta_e \frac{4\pi}{\lambda}\frac{D^2\pi}{4}) = 10\log\left(\eta_e\left(\frac{\pi D}{\lambda}\right)^2\right) = 10\log\left(0.64\left(\frac{5\pi}{0.0212}\right)^2\right)$$

- Pr can be calculated from the 1st and 2nd equation.

The only unknown now is Pt which can be now solved from 3rd equation.

Satellite Comms Link Design procedure

- Determine the frequency band in which the system is going to operate
- Determine parameters for the satellite and estimate any values that are not known
- Determine parameters of receiving and transmitting earth stations
- Start at the transmitting earth station. Establish an uplink budget and transponder noise power budget to find $(C/N)_{up}$ at the transponder.
- Find the output power at the transponder based on transponder gain
- Establish downlink power and noise budget; calculate $(C/N)_{down}$ and $(C/N)_0$
- Calculate S/N and BER at the baseband channel
- Examine and compare the result with the specification; Change parameters to obtain acceptable $(C/N)_0$
- Determine propagation conditions
- Redesign if link margins are inadequate.

Overview

Introduce **Multiple Access techniques** that are commonly used to access large number of users

Multiple Access Techniques

- The ability of satellite to carry many signals at the same time is known as multiple access.
- Multiple access allows communication capacity of the satellite to be shared among a large number of earth stations and to accommodate different types of comms traffic that are transmitted by the earth stations.
- The signals that earth stations transmit may be very different – voce, data, video – but they can be send to the same satellite using multiple access and multiplexing techniques.
- Multiplexing is a process of combining a number of signals into a single signal so that it can be processed by a single amplifier and transmitted over a single channel.
- Multiplexing can be done at a baseband signal or at a radio frequency.

- The choice of multiple access technique will influence the capacity and flexibility of the satellite system, its cost and revenue.
- The aim is to allow a changing number of earth stations to share the satellite in a way that maximises capacity, uses bandwidth efficiently, is flexible, cost to user is minimised whilst the revenue is maximised.
- There are 3 different multiple access techniques (also used in other comms systems):
- **Frequency Division Multiple Access (FDMA)**
  - Satellite, Broadcast Radio and TV, 1st generation analogue mobile systems

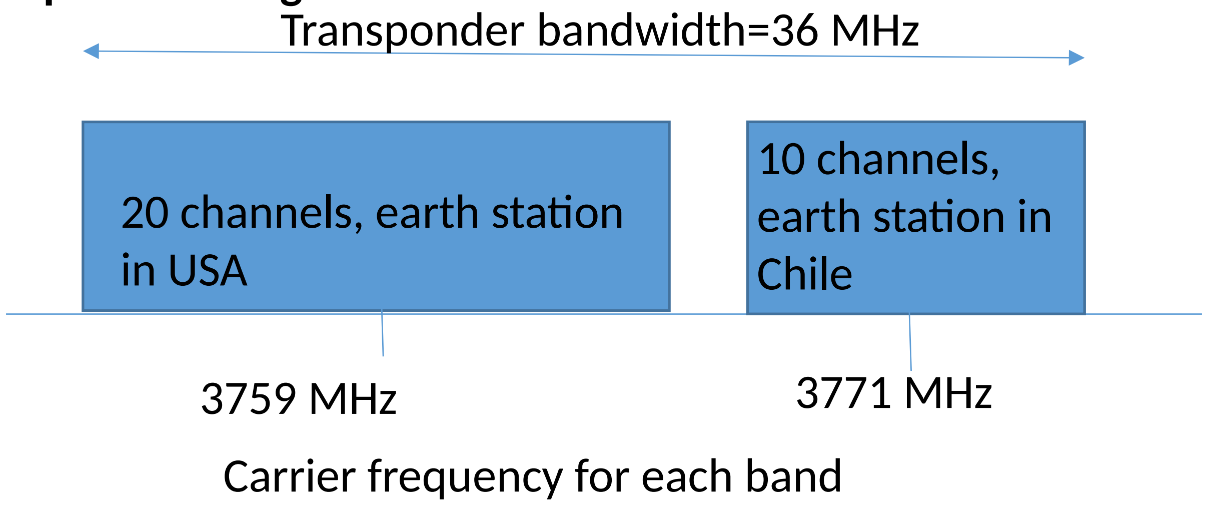
- **Time Division Multiple access (TDMA)**
  - Satellite, 2nd generation mobile, GSM, D-AMPS or IS-126

- **Code Division Multiple Access (CDMA)**
  - 2nd generation mobile IS-95, 3rd generation mobile, satellite

Frequency Division Multiple Access (FDMA)

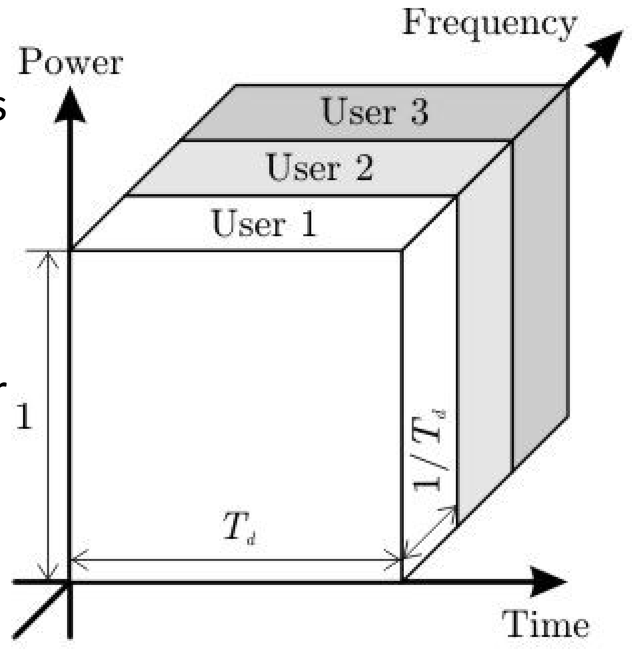
- FDMA is the 1st multiple access technique used in satellite communications.
- FDMA underlines all systems (TDMA and CDMA) and can be used with analogue or digital signals.
- Each user is allocated a frequency band on demand.
- The main advantage of FDMA is that filters are used to separate channels – filter technology well understood when satellite comms began.
- Each transmitting earth station was allocated a frequency and bandwidth for a group of signals that it needs to send (typically a number of telephone channels are grouped together and modulated by a fixed high frequency carrier).

C-band transponder using FDMA



FDMA

- Filters used to separate signals within a given transponder. Circuit complexity is low, but need good (expensive) filters and duplexers.
- Does not require channel equalisation (time spreading of signals is low).
- No synchronisation information is required.
- Use of microwave filters require that assignment of channels is fixed. Changing of frequency or bandwidth of any or transmitting earth stations means that microwave filters need to be re-tuned.
- Fixed channel assignment also means inefficient use of transponder bandwidth. For example consider an earth station in USA that uses Pacific Ocean GEO satellite to send telephone signals to Japan, Korea and Chile. Traffic between USA and Japan will be used only a few hours of day due to time difference and at different time than traffic with Chile. Unused channels sit idle as we cannot reallocate channels and frequencies between different routes. Average loading of a satellite is around 15% - it can never be 100%.
- FDMA has a disadvantage when transponder has a nonlinear characteristic. This is typical when travelling wave tube amplifier (TWTA) is used instead of solid state high-power amplifier (SSHPA);
- Nonlinearity causes a reduction in overall C/N when FDMA is used because intermodulation products are generated in the transponder. IM products can fall in the bandwidth and cause interference and they are treated as noise and they add to the total noise in the system.



All channels are transmitted at the same time.

FDMA

Unallocated channels sit idle!

Intermodulation

- Satellite transponder is driven close to the saturation point where their operation is non-linear.
- TWTA are more prone to nonlinearities than solid state high power amplifiers.
- Third order IM products often fall in the bandwidth of desired signal.
- Output voltage from a nonlinear amplifier has a cubic voltage relationship as:

$$V_{out} = AV_{in} + bV_{in}^3$$

- If the input voltage consists of two unmodulated carriers at frequencies f1 and f2:

$$V_{in} = V_1 \cos(\omega_1 t) + V_2 \cos(\omega_2 t)$$

- The output signal is:

$$V_{in} = \underbrace{AV_1 \cos(\omega_1 t) + AV_2 \cos(\omega_2 t)}_{\text{Linear term}} + \underbrace{b(V_1 \cos(\omega_1 t) + V_2 \cos(\omega_2 t))^3}_{\text{Cubic term}}$$

- The cubic term can be expanded as:

$$V_{3out} = b(V_1 \cos(\omega_1 t) + V_2 \cos(\omega_2 t))^3 =$$

$$b\begin{pmatrix} V_1^3 \cos^3(\omega_1 t) + V_2^3 \cos^3(\omega_2 t) + \\ 2V_1^2 \cos^2(\omega_1 t) \cdot V_2 \cos(\omega_2 t) + 2V_2^2 \cos^2(\omega_2 t) \cdot V_1 \cos(\omega_1 t) \end{pmatrix}$$

The 1st two terms have frequencies at f_1, f_2, $3f_1$ and $3f_2$; Triple frequency components can be removed using band pass filters.

Lets expand the 3rd term:

$$bV_1^2V_2\cos^2(\omega_1 t)\cdot\cos(\omega_2 t) = bV_1^2V_2\cos(\omega_2 t)\cdot(\cos(2\omega_1 t)+1) =$$
$$bV_1^2V_2\cos(\omega_2 t)\cos(2\omega_1 t)+\cos(\omega_2 t) = bV_1^2V_2\left[\cos(2\omega_1 t+\omega_2 t)+\cos(2\omega_1 t-\omega_2 t)\right]$$

Frequency ($2f_1+f_2$) can be filtered out but the frequency ($2f_1-f_2$) will fall within transponder bandwidth and represents the 3rd order intermodulation product.

Similarly from the 4th term we have intermodulation products at frequencies $2f_2+f_1$ and $2f_2-f_1$. Only $2f_2-f_1$ is unwanted intermodulation product that will mix with the channels in the same bandwidth.

Example:

The C-band transponder has 36MHz bandwidth and an output spectrum for downlink signals in the frequency range 3705-3741MHz.

a) The transponder carries two unmodulated carriers at 3718MHz and 3728MHz with equal amplitudes at the input to HPA. Find the frequencies that fall within the transponder bandwidth.

b) The transponder carries two modulated signals with 8MHz bandwidth in the range 3714-3722MHz and 3726-3734MHz. Find the spectrum that is occupied by IM products.

Solution:

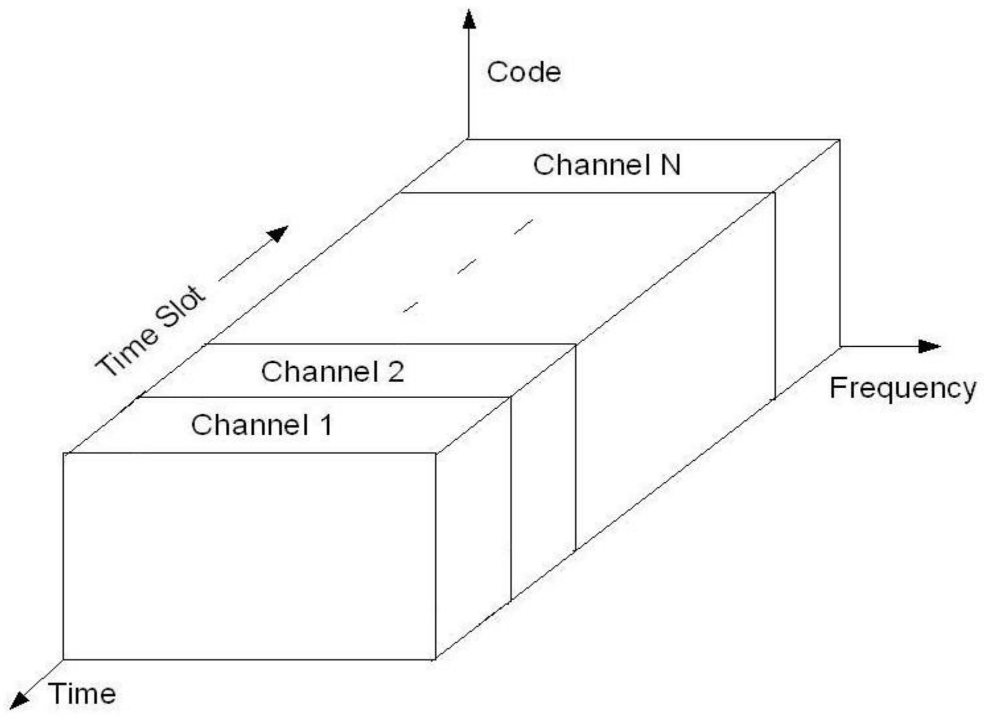
a) $2f_1$-f_2, $2f_1$-f_2; (3708MHz,3738MHz)

b) $2f_{2lo}$-f_{1hi}, $2f_{2hi}$-f_{2lo} …..test all

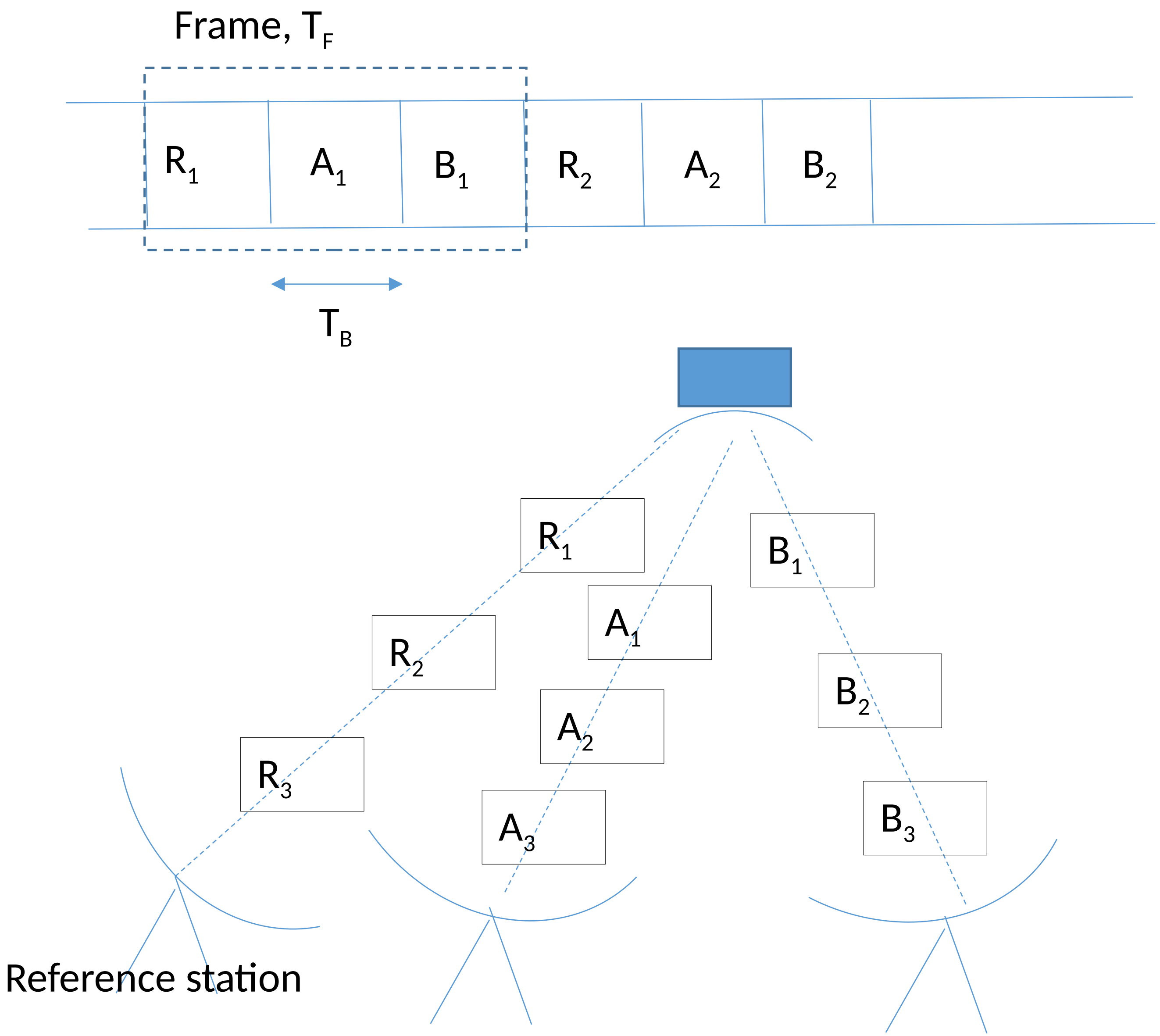
$2f_{1hi}$-f_{2hi} to $2f_{2hi}$-f_{1hi} (3710-3746)MHz

Time Division Multiple Access (TDMA)

- With TDMA only one carrier uses the transponder at any time and therefore intermodulation products are absent.
- This is the biggest advantage of TDMA as TWTA can be operated at maximum power or at a saturation level.
- Signal is transmitted in bursts and TDMA is only suitable for digital signals – signal is assembled into burst format for transmission or re-assembled from the receiving bursts.



TDMA using a reference station for burst synchronisation



The stations transmit bursts in sequence.

One station is used solely for bursts synchronisation and transmits ***reference bursts***.
Each of the station within the network has a time slot within a frame and must maintain its transmission within that time slot.

The time interval from one reference burst to another is called a ***frame***.

To store one frame the buffer must have a capacity M, $M=R_bT_F$ where R_b is the bit rate.

To transmit M bits in the burst time T_B the transmission rate is
$R_{TDMA}=R_bT_F/T_B$

- If digital modulation is used the TDMA system will have to transmit at a higher bit rate compared to FDMA.
- This requires a corresponding increase in C/N for TDMA system compared to the FDMA system .
- If the FDMA system is transmitting at R_b and TDMA system at R_{TDMA}, than the increase in EIRP is:

$$\lfloor EIRP \rfloor_{TDMA} - \lfloor EIRP \rfloor_{FDMA} = \lfloor R \rfloor_{TDMA} - \lfloor R \rfloor_b$$

- For digital system carrier to noise ratio is:

$$\left[\frac{C}{N_0}\right] = \left[\frac{E_b}{N_0}\right] + [R]$$

Example:

A 14GHz uplink operates with transmission losses and margins totalling 212dB and a satellite [G/T]=10dB/K. The required uplink [Eb/No] is 12dB.

a) assuming FDMA operation and an earth-station uplink antenna gain of 46dB, calculate the earth station transmitter power needed for transmission of a baseband signal with a bit rate of 1.544Mb/s.

b) If the downlink transmission rate is fixed at 74dBb/s calculate the uplink power increase required for TDMA operation.

Solution:

a)

R[dB]=20log(R)=20log(1.544*1e6)=62dBb/s

$$\left[\frac{C}{N_0}\right]=\left[\frac{E_b}{N_0}\right]+\left[R\right]=12+62=74dBHz$$

$$\left(\frac{C}{N_0}\right)=\left[\frac{P_tG_tG_r}{kT_sB_n}\right]\left[\frac{\lambda}{4\pi R}\right]^2=\left[\frac{P_tG_t}{kB_n}\right]\left[\frac{\lambda}{4\pi R}\right]^2\left[\frac{G_r}{T_s}\right]$$

$$\left[EIRP\right]=\left[\frac{C}{N_0}\right]-\left[\frac{G_r}{T_s}\right]-\left[\frac{\lambda}{4\pi R}\right]^2+\left[losses\right]=74-10-229+212=47dBW$$

$$\left|EIRP\right|=P_tG_t \Rightarrow P_t=\left|EIRP\right|-G_t=47-46=1W$$

b)

$$\lfloor EIRP\rfloor_{TDMA}-\lfloor EIRP\rfloor_{FDMA}=\lfloor R\rfloor_{TDMA}-\lfloor R\rfloor_{b}$$

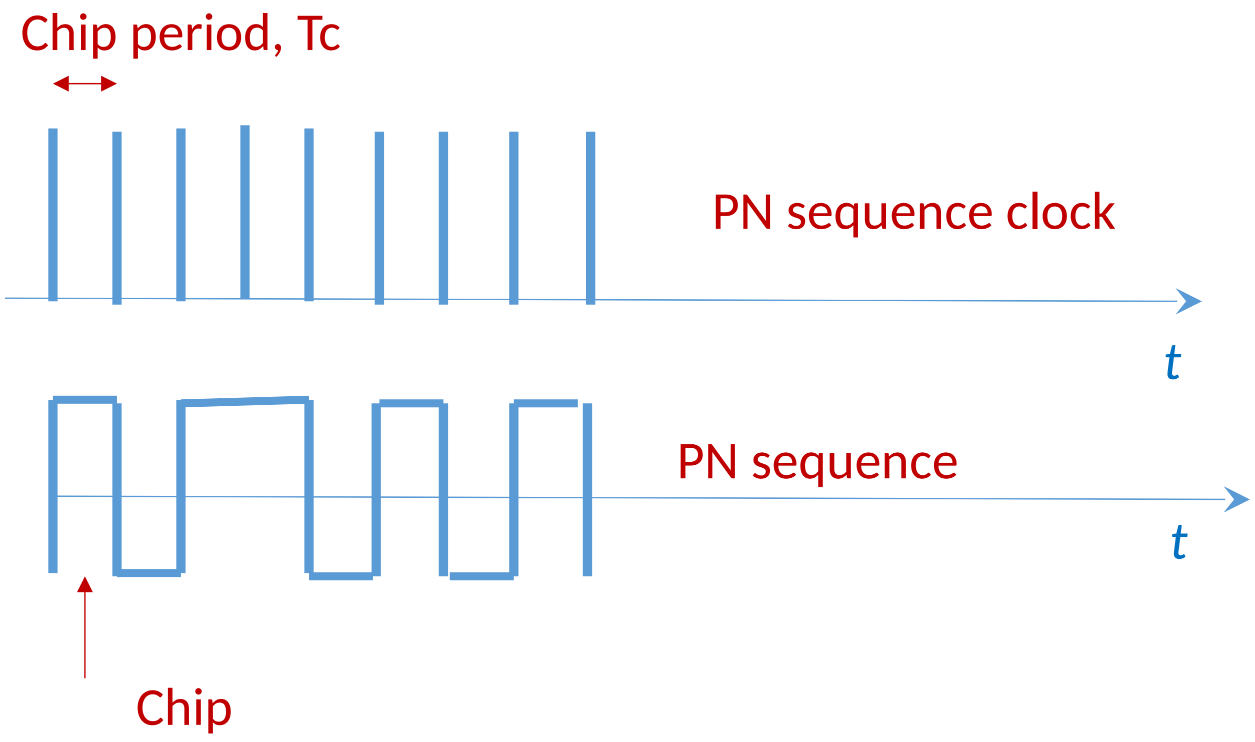
R_{TDMA}-R_b=74-62=12[dB]

Code Division Multiple Access (CDMA)

- CDMA is using so called spread spectrum technology that has been developed for military comms systems.
- Individual carriers may be present simultaneously within the same RF bandwidth but each carrier carries a unique code waveform that allows it to be separated from all others at the receiver.
- The carrier is modulated in the normal way by the information waveform (baseband signal) and then is further modulated by the code waveform ***to spread*** the signal over the available RF bandwidth – ***spread spectrum multiple access***.
- The spread spectrum can be viewed as a modulation scheme – signal bandwidth is much larger than the message bandwidth.
- Codes are orthogonal which means that they do not interfere (mix)
    - Difficult to intercept
    - Resistant to jamming
    - Immune to distortion due to multipath propagation
    - Multiple access capability (TDMA/FDMA can be used)

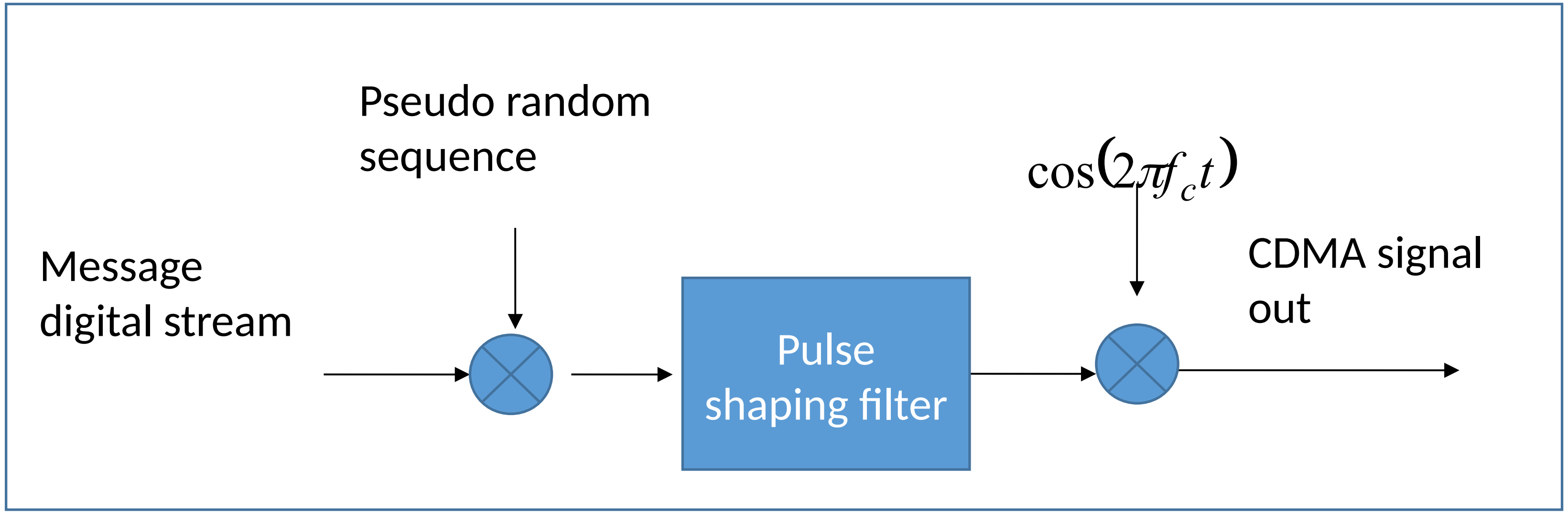
CDMA

- The pseudo-random (PN) sequence has spectral properties of noise.
- The data rate of PN sequences is caller the chip rate.
- At the receiver the incoming signal is correlated with the appropriate code word of user whose message is to be extracted.
- All other messages appear as a noise at the input of receiver. The noise level is increased linearly with number of users.



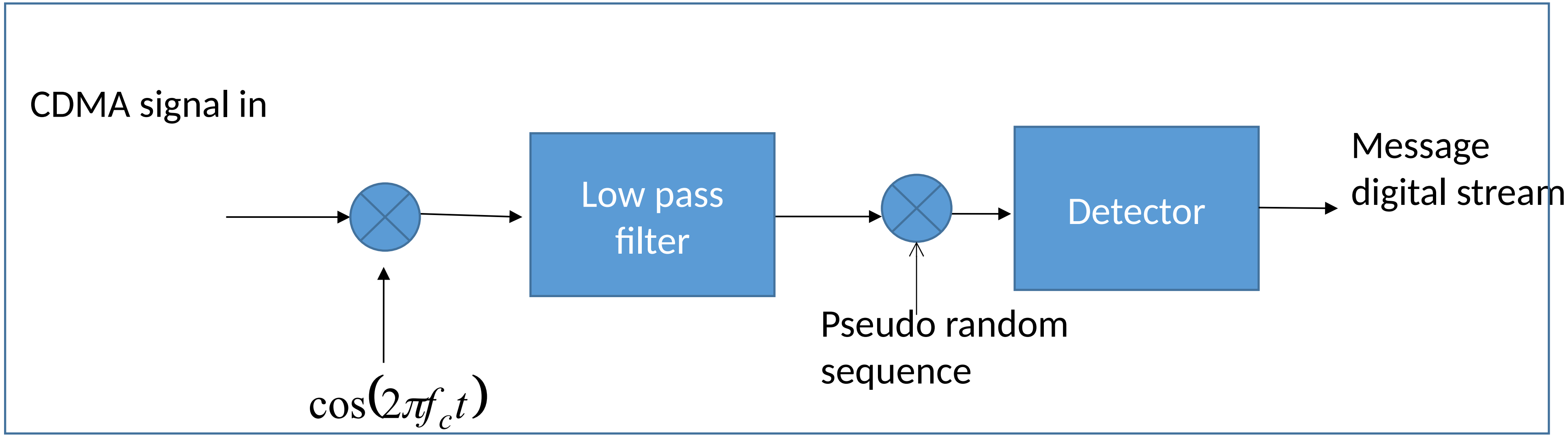
CDMA transmitter

- The CDMA can be viewed as a modulation scheme – signal is multiplied with a pseudo random sequence.
- The CDMA signal has much larger bandwidth than the original message.



CDMA transmitter

CDMA receiver



Conclusions

- Satellite link design
    - Uplink
    - Downlink

- Multiple Access Techniques
    - FDMA
    - TDMA
    - CDMA